MiniBooNE/LSND Neutrino Oscillation Results

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Workshop on Beyond Three Family Neutrino Oscillations
May 3-4, 2011, LNGS (Italy)

Outline of this talk

1. LSND $\bar{\nu}_\mu \to \bar{\nu}_e$
(1993-2001)

2. MiniBooNE $\nu_\mu \to \nu_e$
(2001-2007)

3. MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$
(2006-2010)

4. MiniBooNE $\nu_\mu \to \nu_\mu$
and $\bar{\nu}_\mu \to \bar{\nu}_\mu$
(2001-2011)

5. Light sterile neutrino
oscillations: where we stand
(2011)

LSND $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

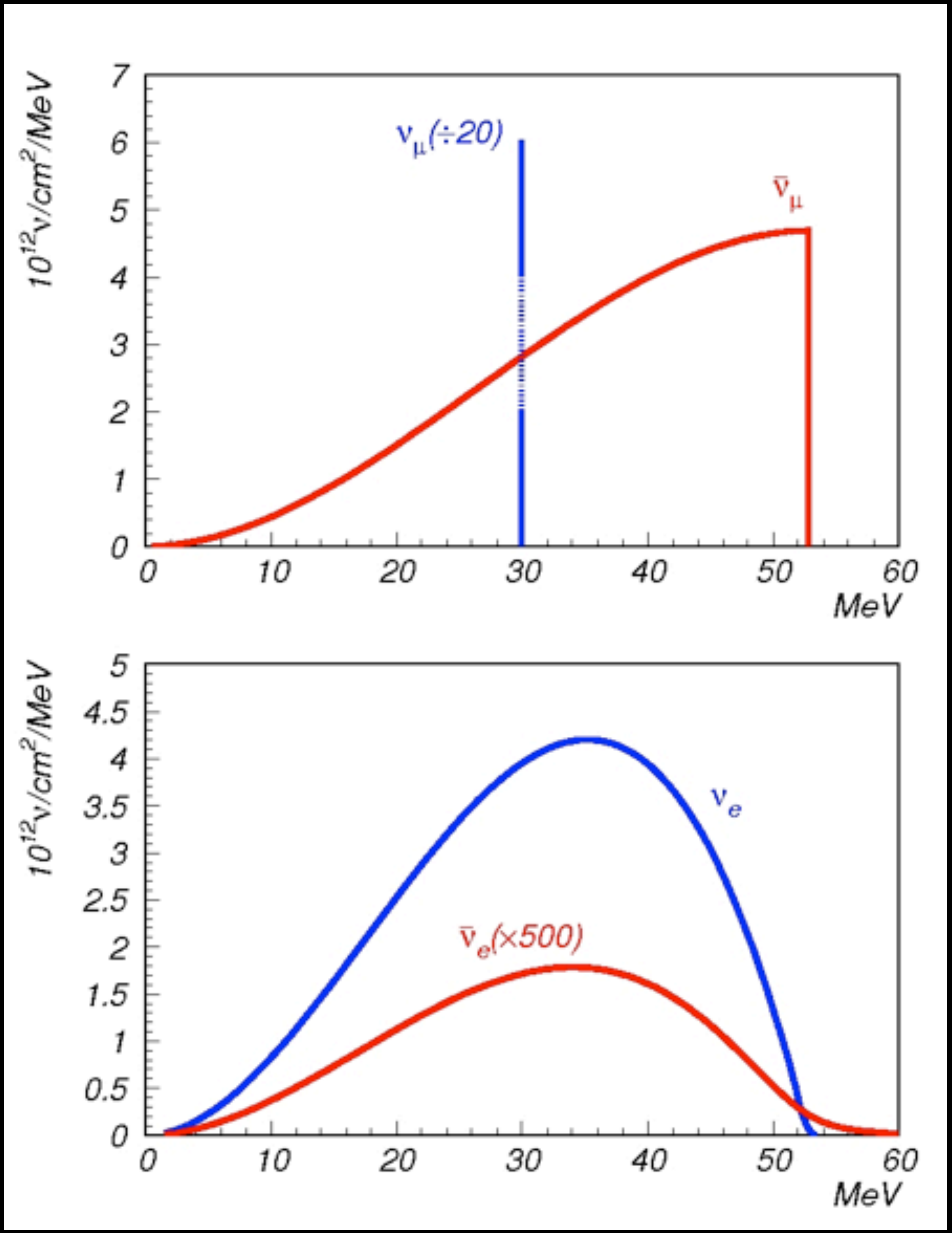
The LSND Experiment

Stopped pion beam meutrino source:

•$\bar{\nu}_\mu$ from: $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

•E_ν = 20 - 53 MeV

•Almost no $\bar{\nu}_e$ at source



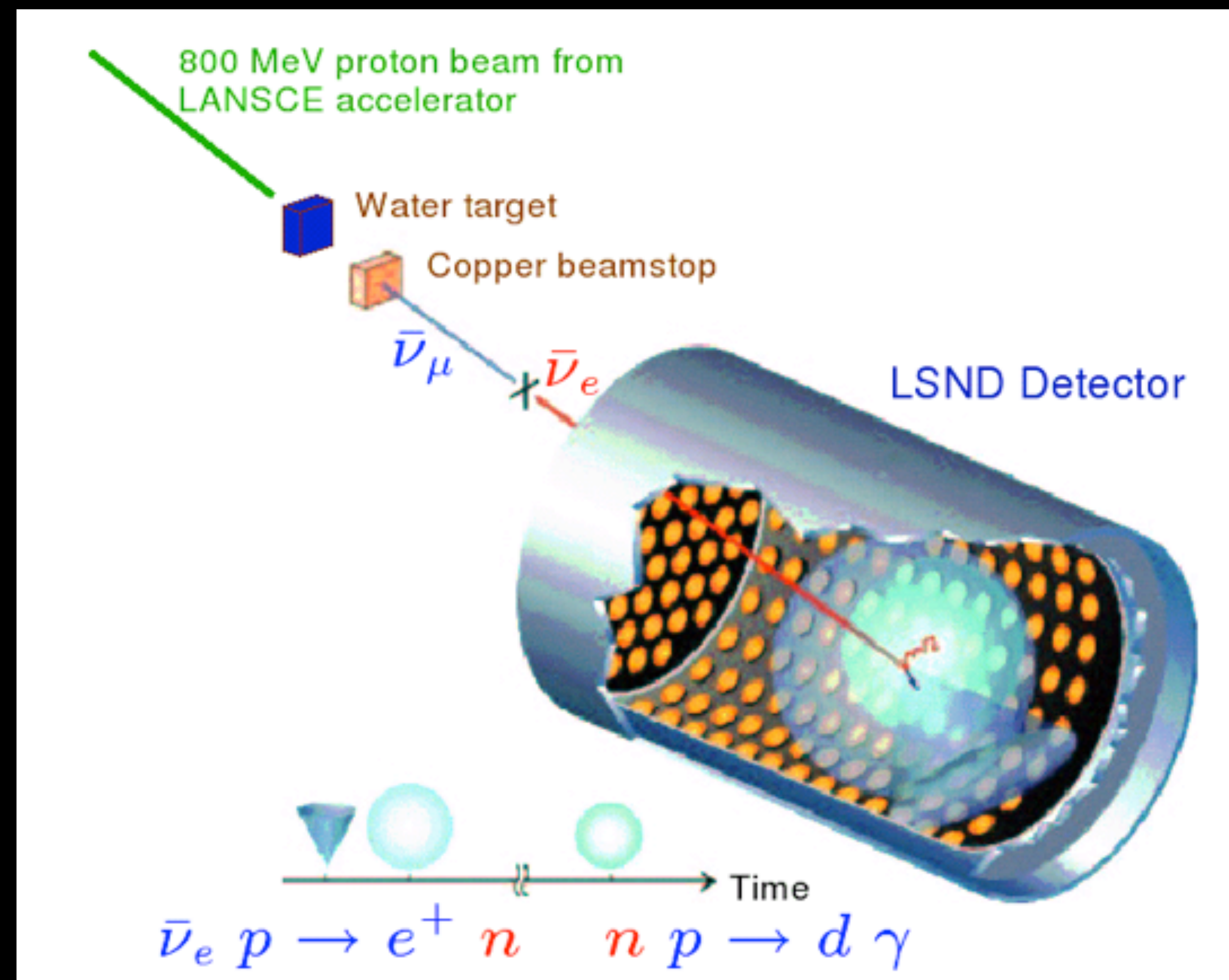
The LSND Experiment

Liquid Scintillator Neutrino Detector:

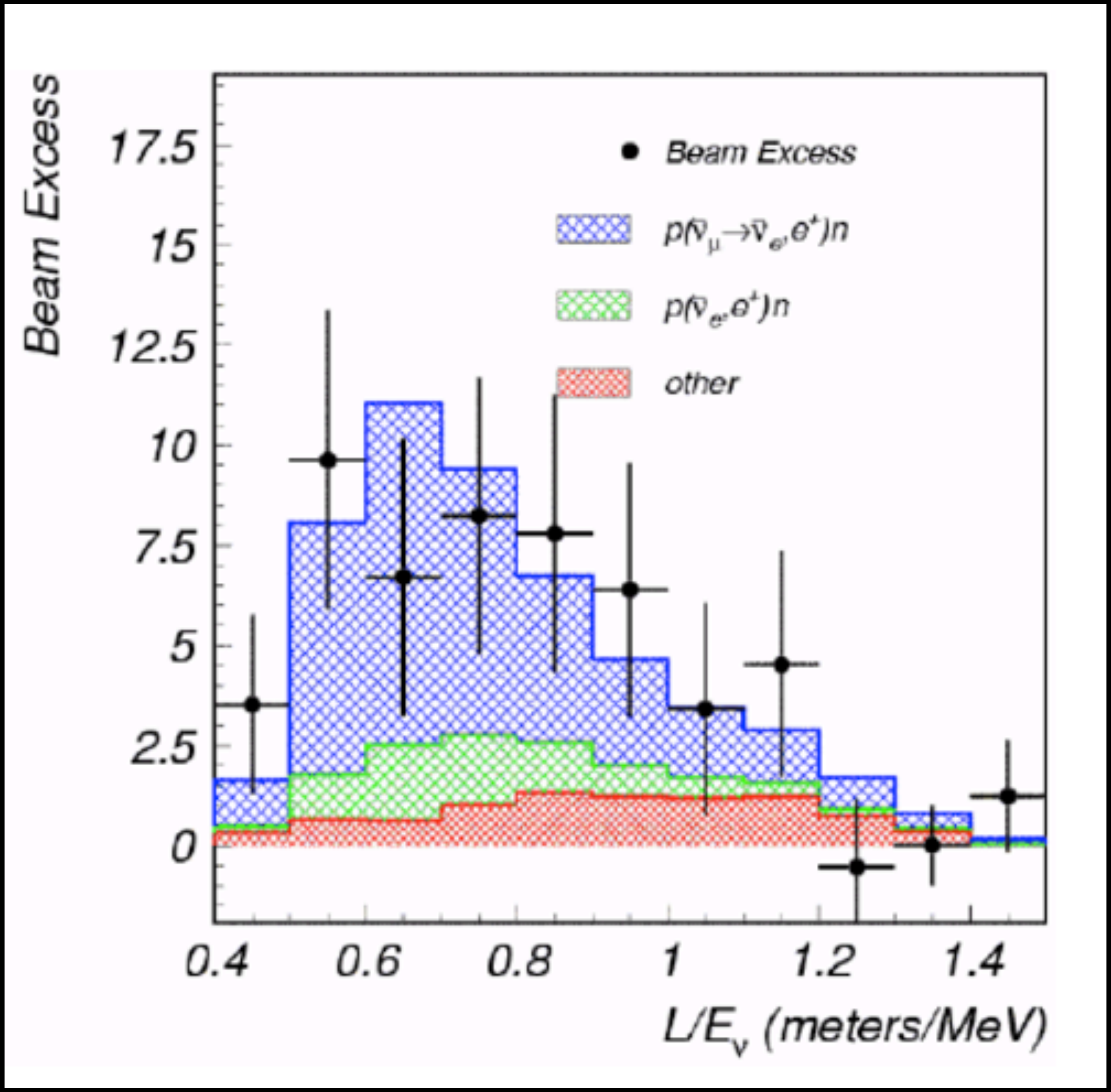
•L_ν = 25-35 m

•For $\bar{\nu}_e\ p \rightarrow e^+\ n$ interactions, detect:

- •Cherenkov/scintillation light from e^+
- •Scintillation light from n capture



The LSND Result



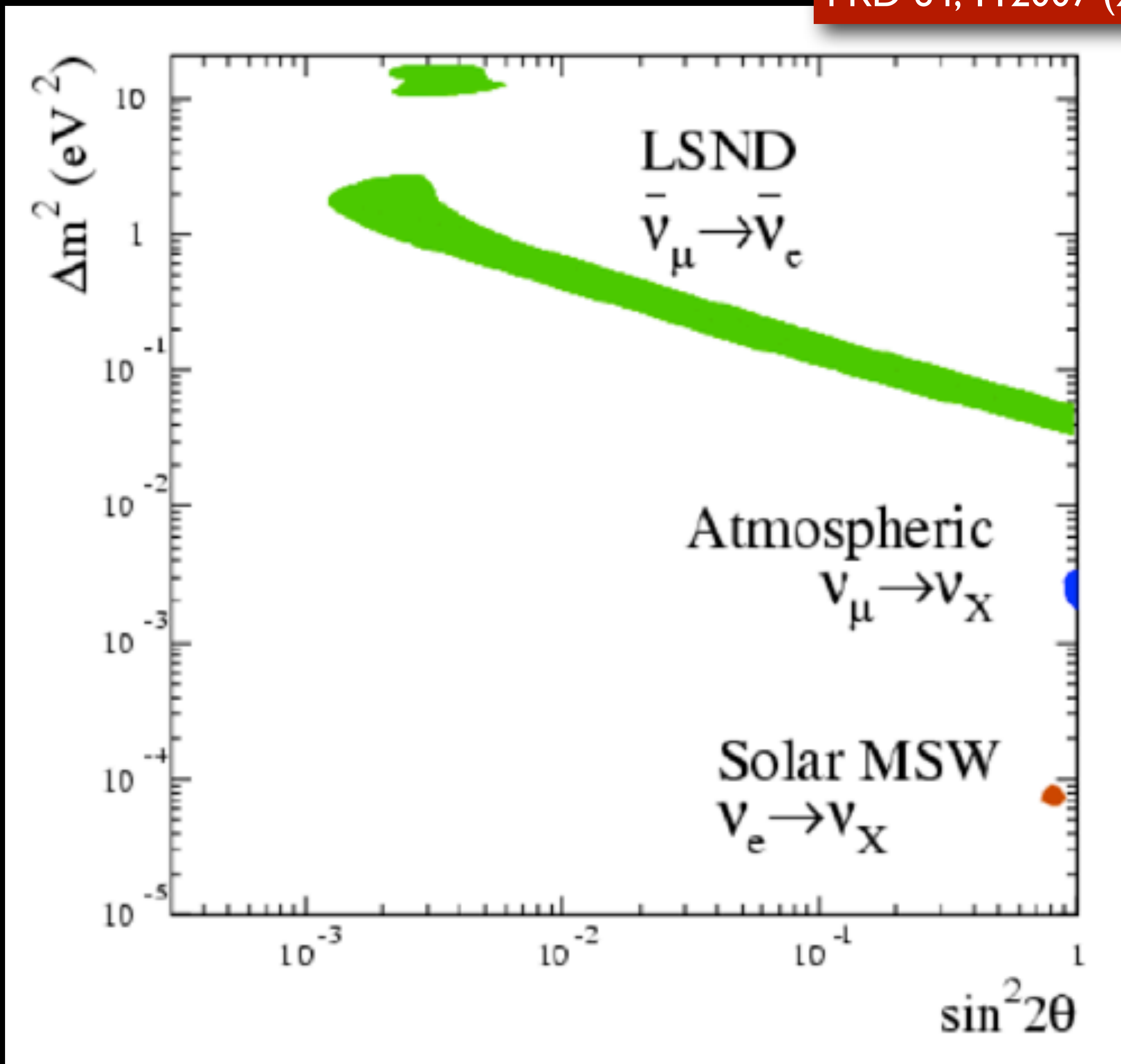
- $\bar{\nu}_e$ candidate excess: $87.9 \pm 22.4 \pm 6.0$ (3.8σ)

- If interpreted as oscillations: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$

PRD 64, 112007 (2001)

The LSND Result

PRD 64, 112007 (2001)



- Mass and mixing parameters:
  - Δm^2 ~0.1-10 eV^2, small mixing
  - Large ($\sin^2 2\theta$, Δm^2) degeneracy

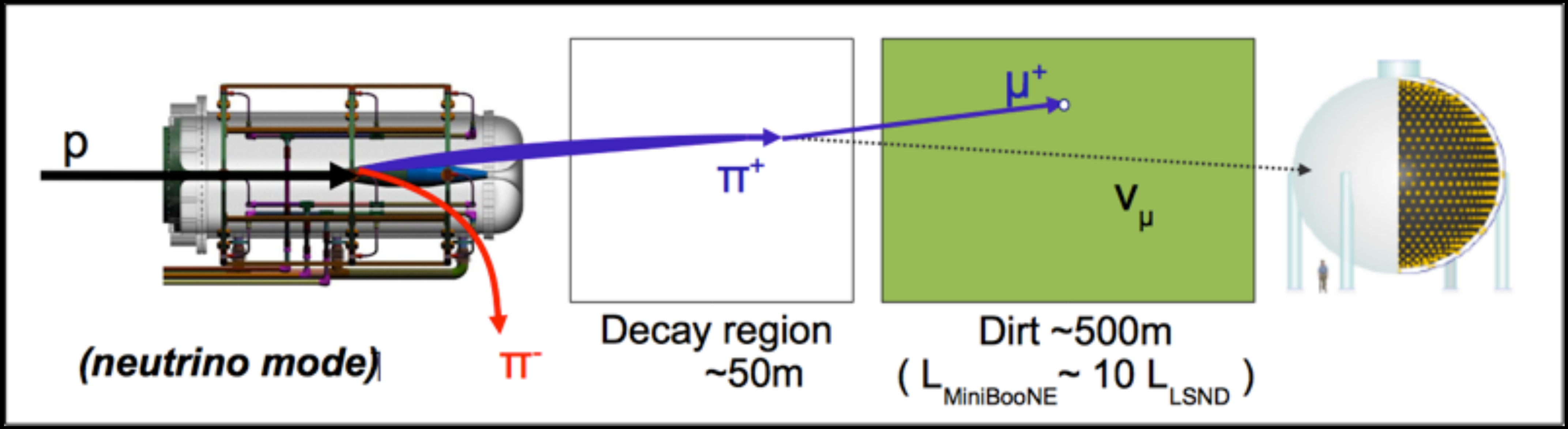
- $\Delta m^2_{LSND} >> \Delta m^2_{atm} + \Delta m^2_{sol}$ and Δm^2_{LSND} ~1 eV^2:

cannot be explained within standard (eg, no steriles) neutrino physics and cosmology paradigms

Needs confirmation! Motivation for MiniBooNE

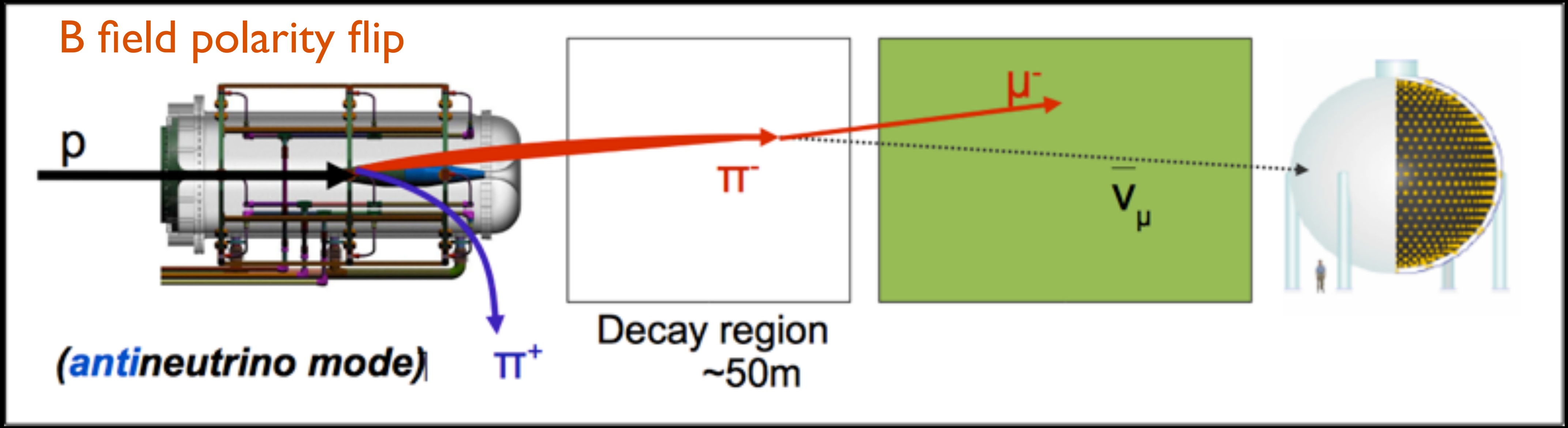
The MiniBooNE Recipe For Appearance Searches

Two Searches: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



makes a primarily ν_μ beam

Or...



makes a primarily $\bar{\nu}_\mu$ beam

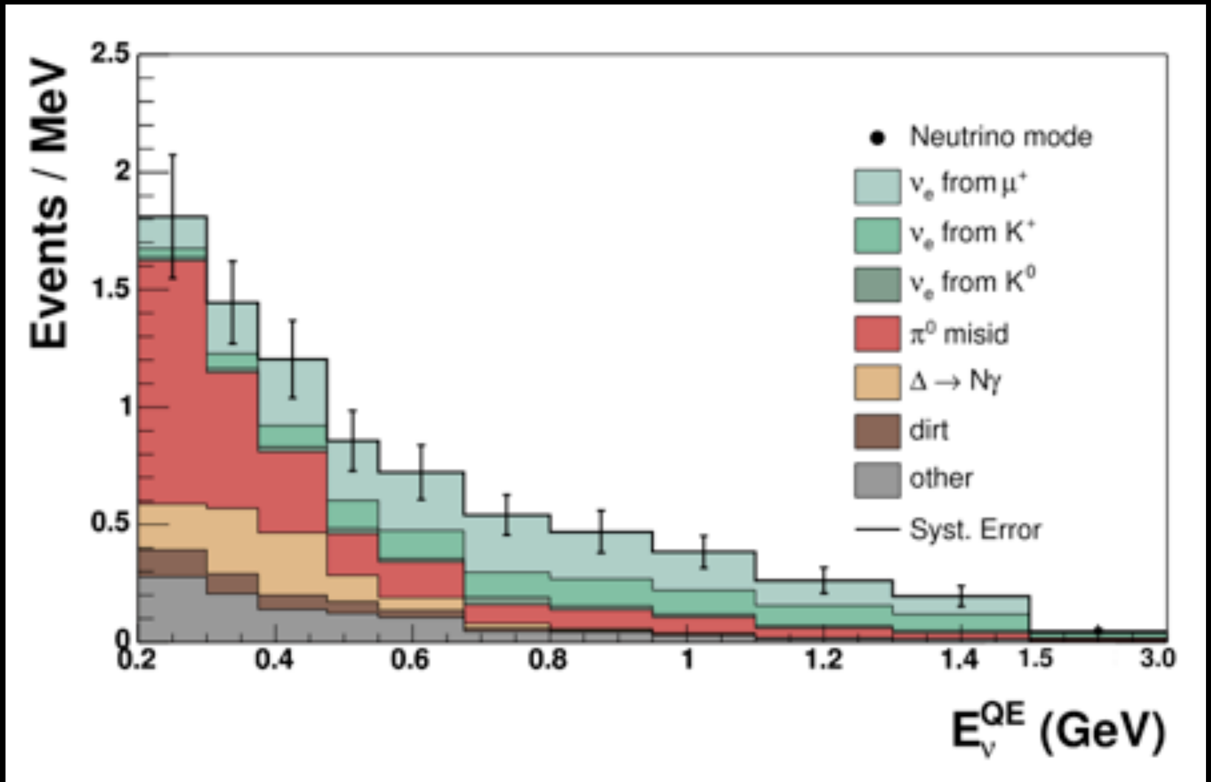
Two Searches: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Two separate searches, one in neutrino mode and one in antineutrino mode

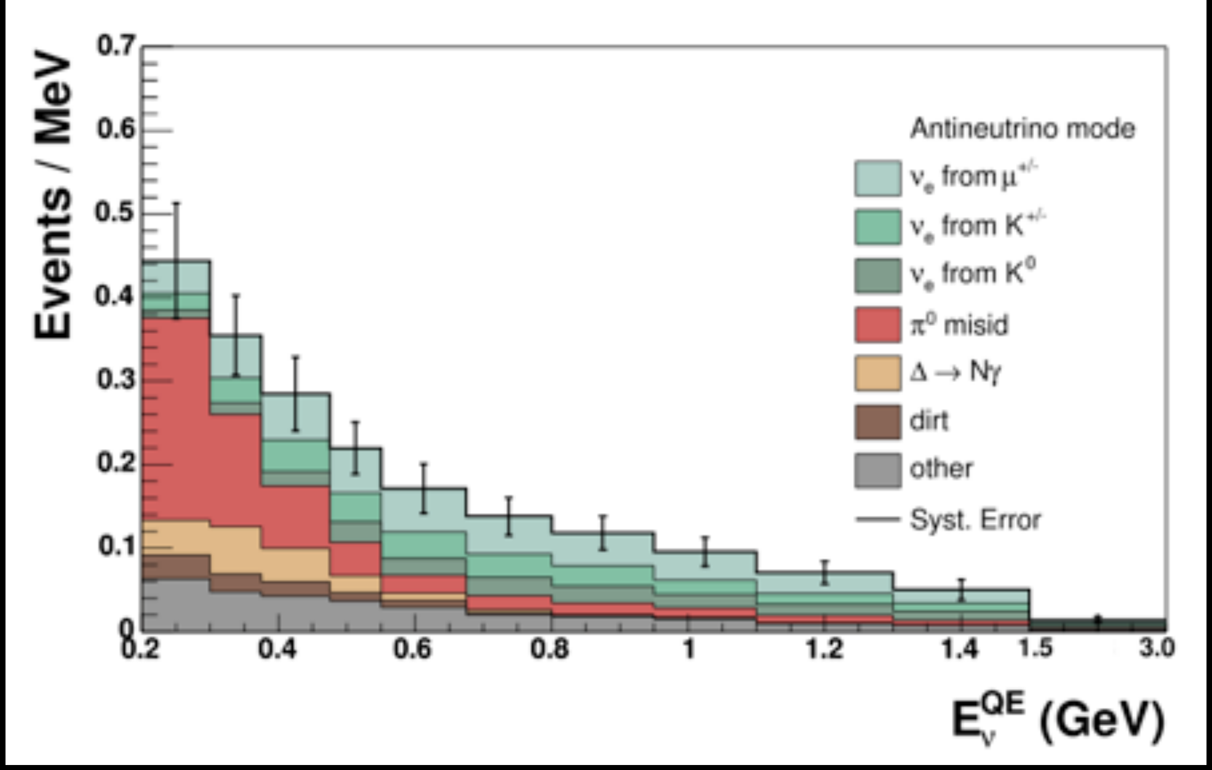
Look for appearance of ν_e or $\bar{\nu}_e$ events above background expectations versus energy, and see if described by a two-neutrino oscillation hypothesis

versus energy, and see if described by a two-neutrino oscillation hypothesis

Expected background neutrino mode



Expected background antineutrino mode



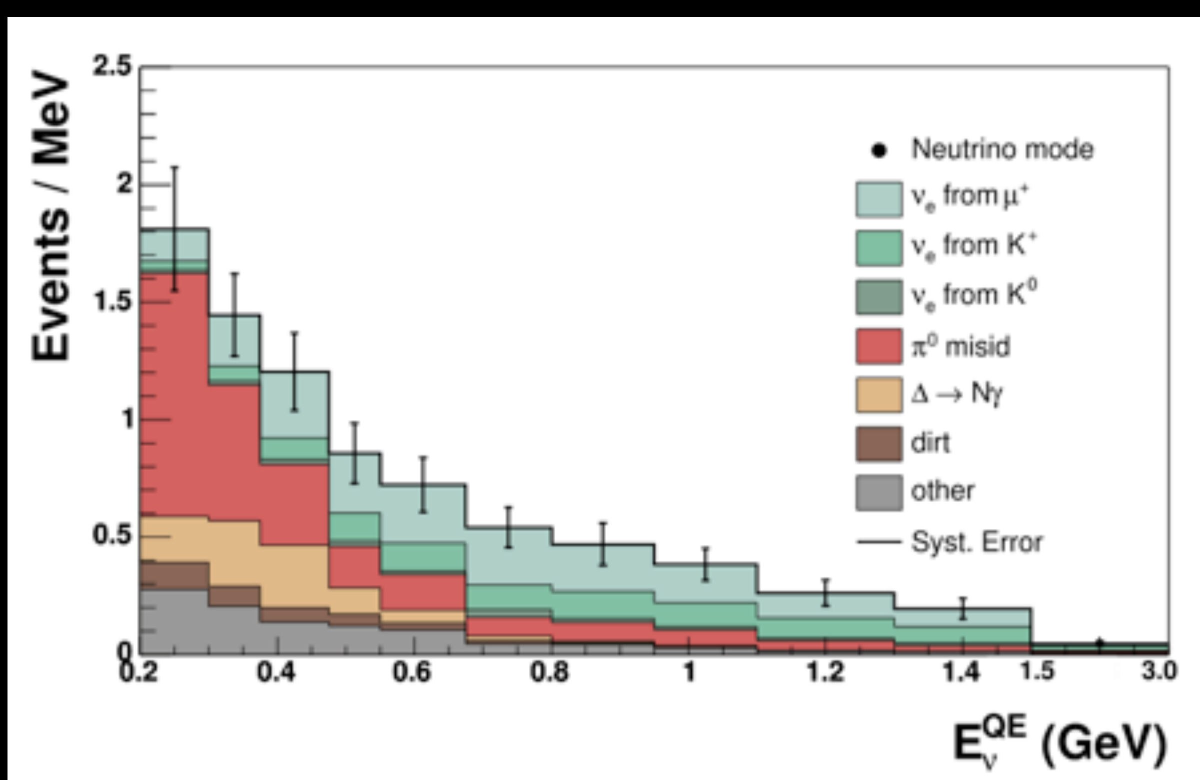
Two Searches: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Two separate searches, one in neutrino mode and one in antineutrino mode

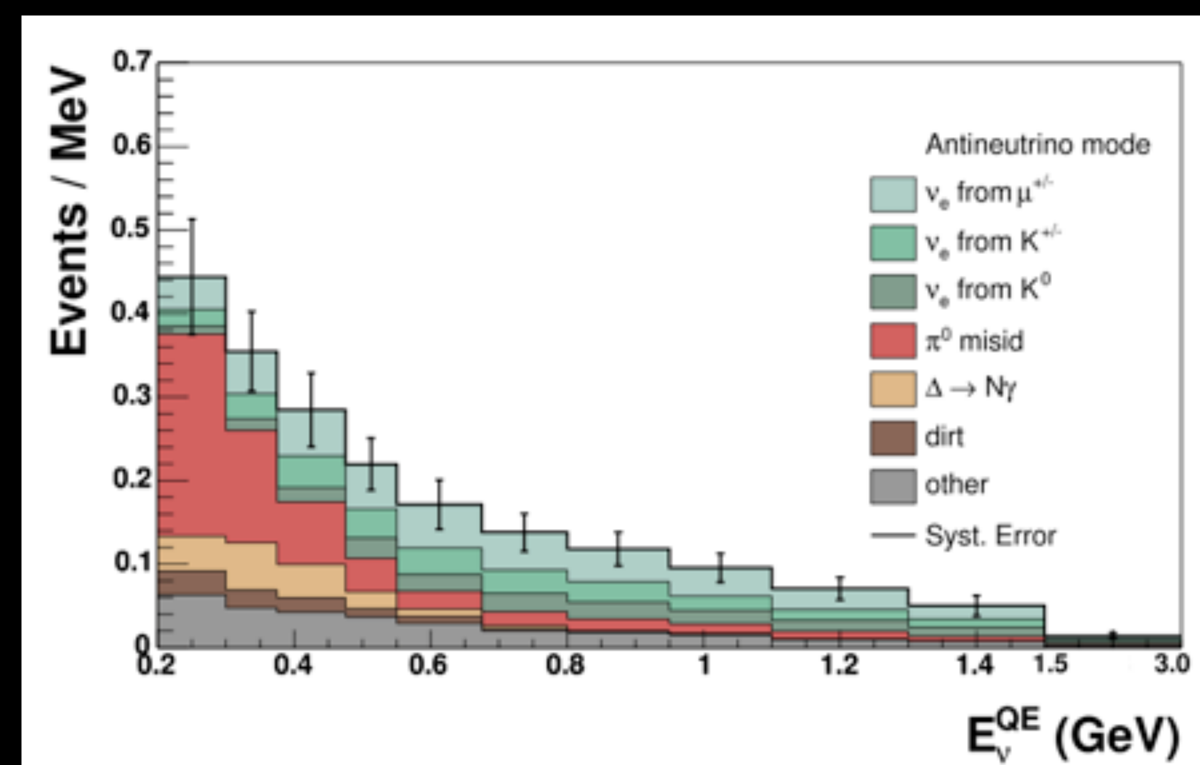
High statistics, powerful test of LSND's simplest interpretation

Lower statistics (less powerful), but direct test of LSND excess

Expected background neutrino mode



Expected background antineutrino mode



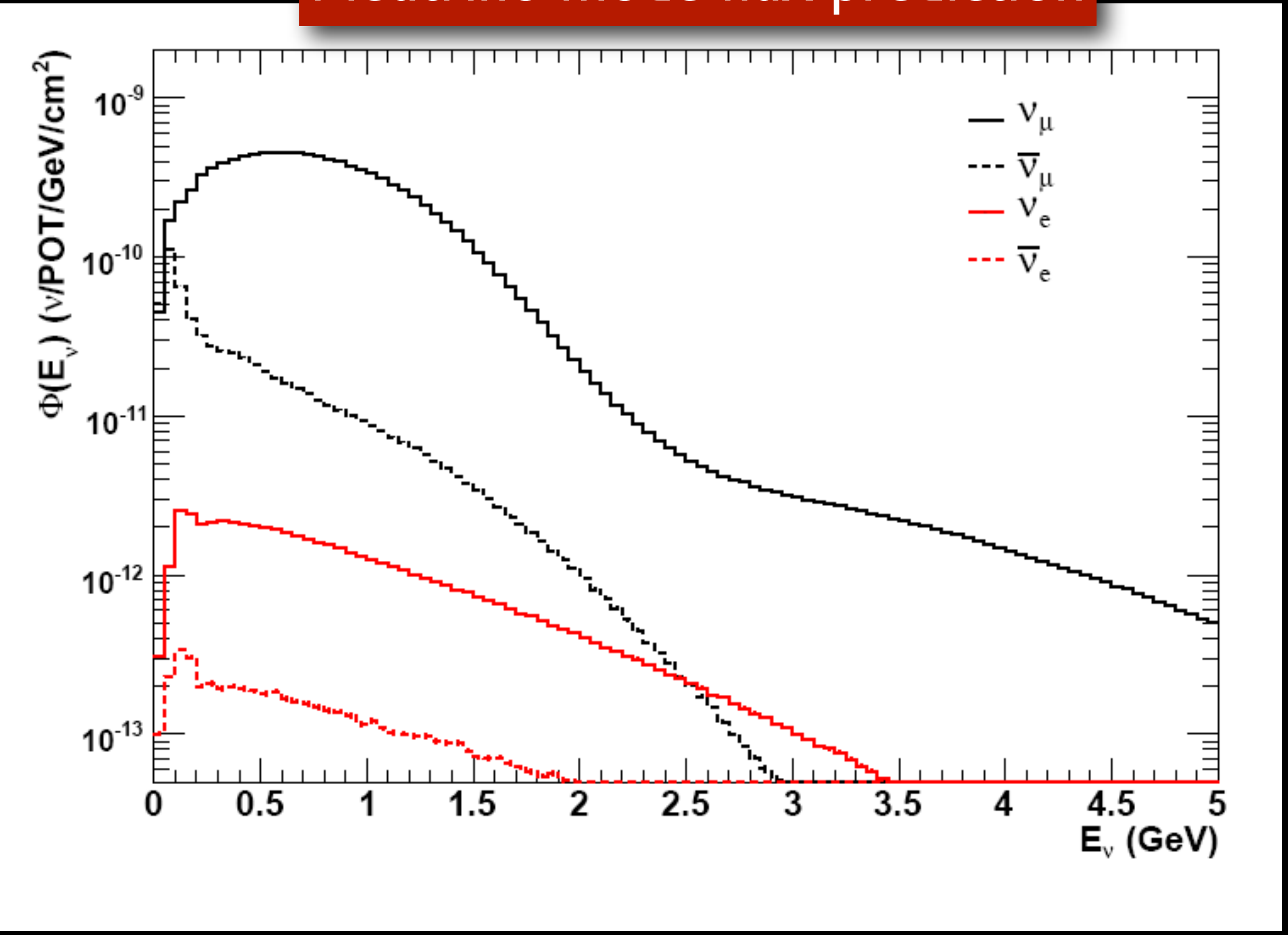
The MiniBooNE Recipe For Appearance Searches

Ingredients:

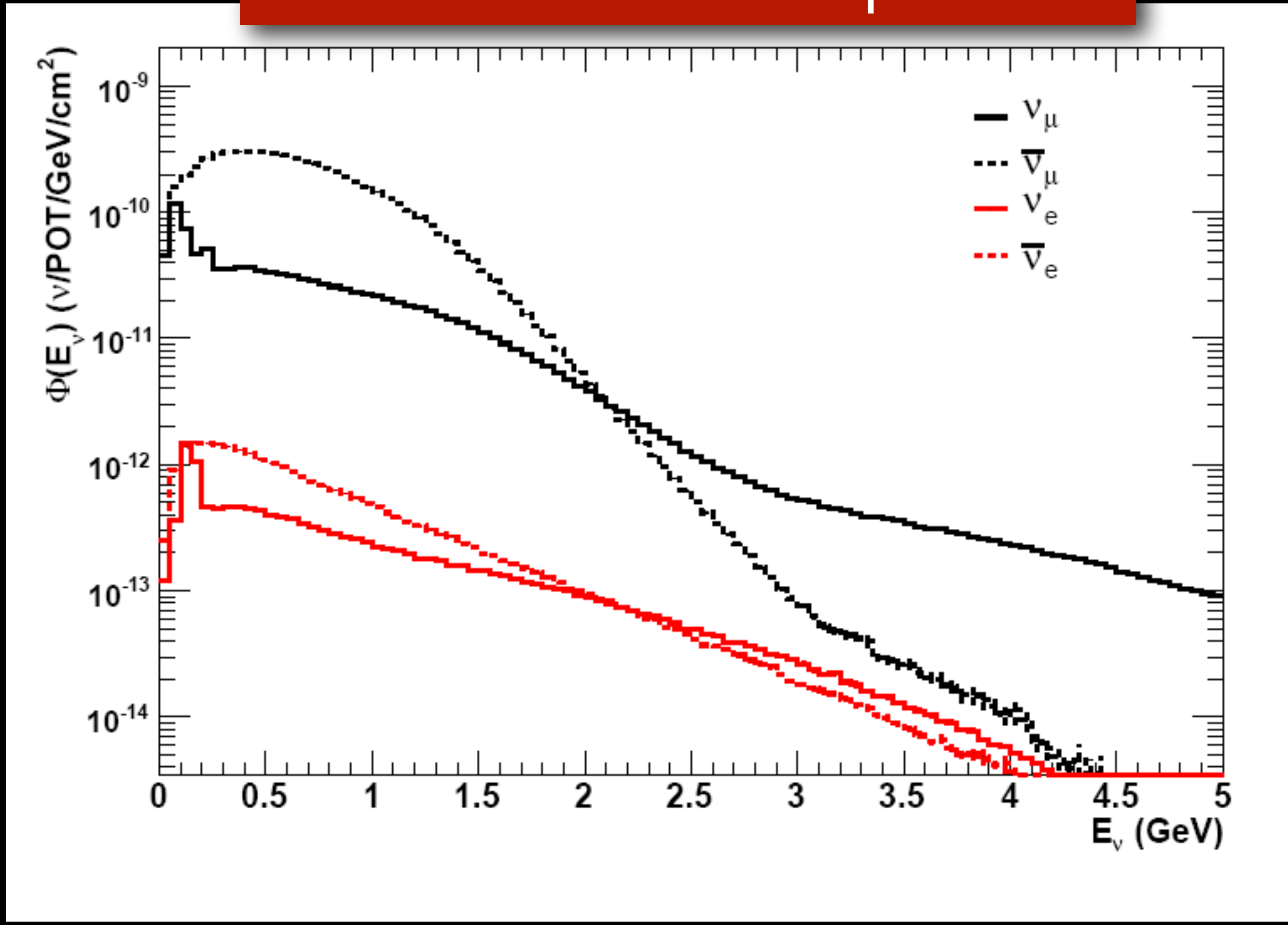
- Same L/E as LSND
- High intensity ν_μ beam with low intrinsic ν_e contamination
- Powerful neutrino flavor tagging (ν_μ .vs. ν_e interaction)
- Information about neutrino energy spectrum
- Patience (& data stability)

- Same L/E as LSND
- High intensity ν_μ beam with low intrinsic ν_e contamination

Neutrino mode flux prediction

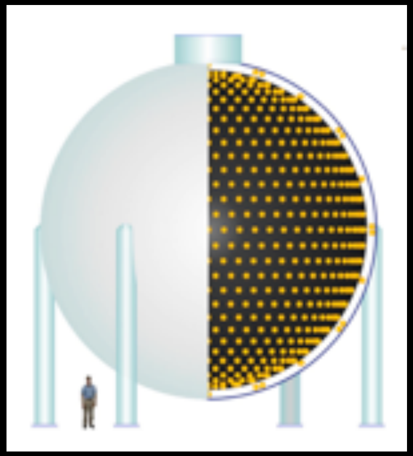


Antineutrino mode flux prediction



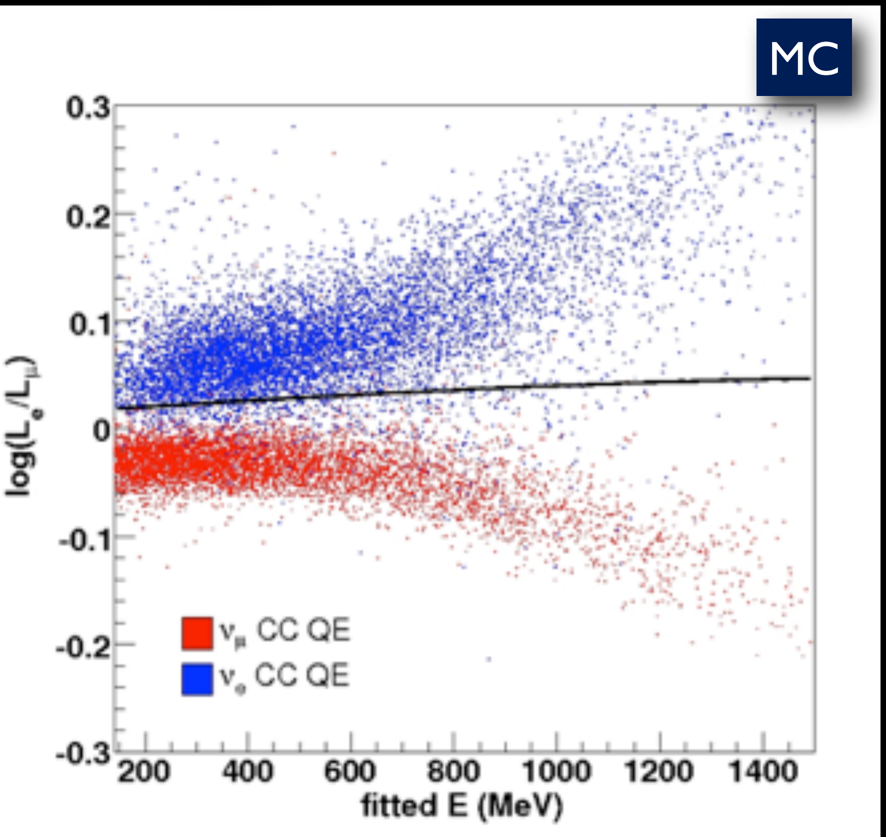
- Neutrino flux peaks at E_ν~0.4-0.7 GeV, and extends up to 2-3 GeV
- Intrinsic ν_e contamination ~0.6% in both running modes
- Collected >10^{21} protons on target!

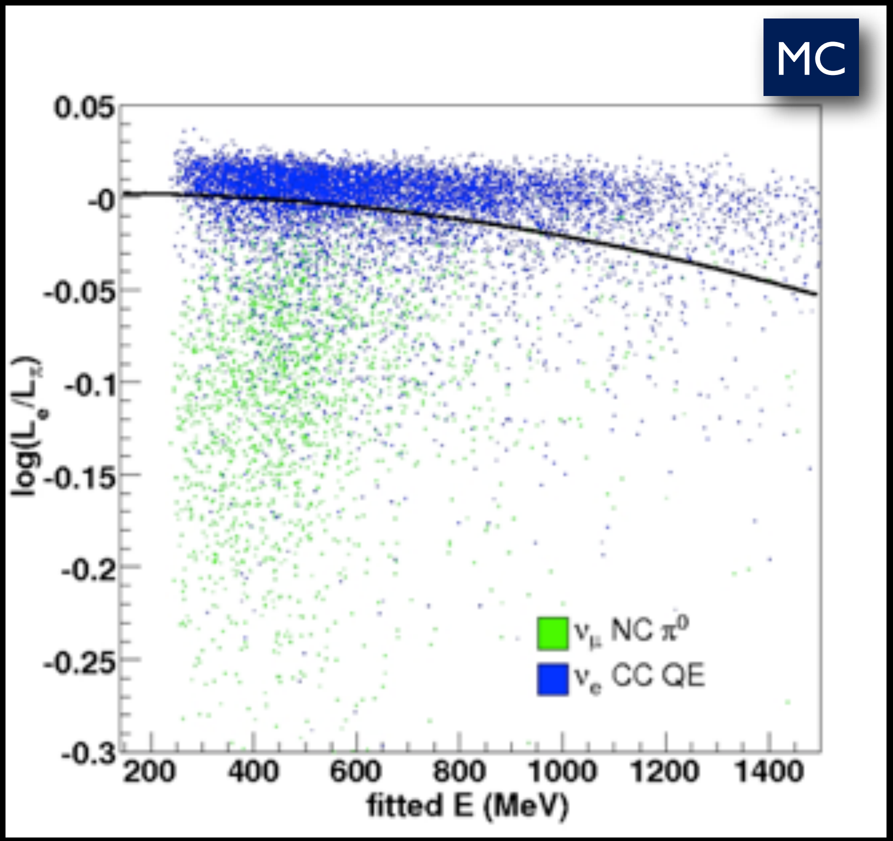
MiniBooNE Detector

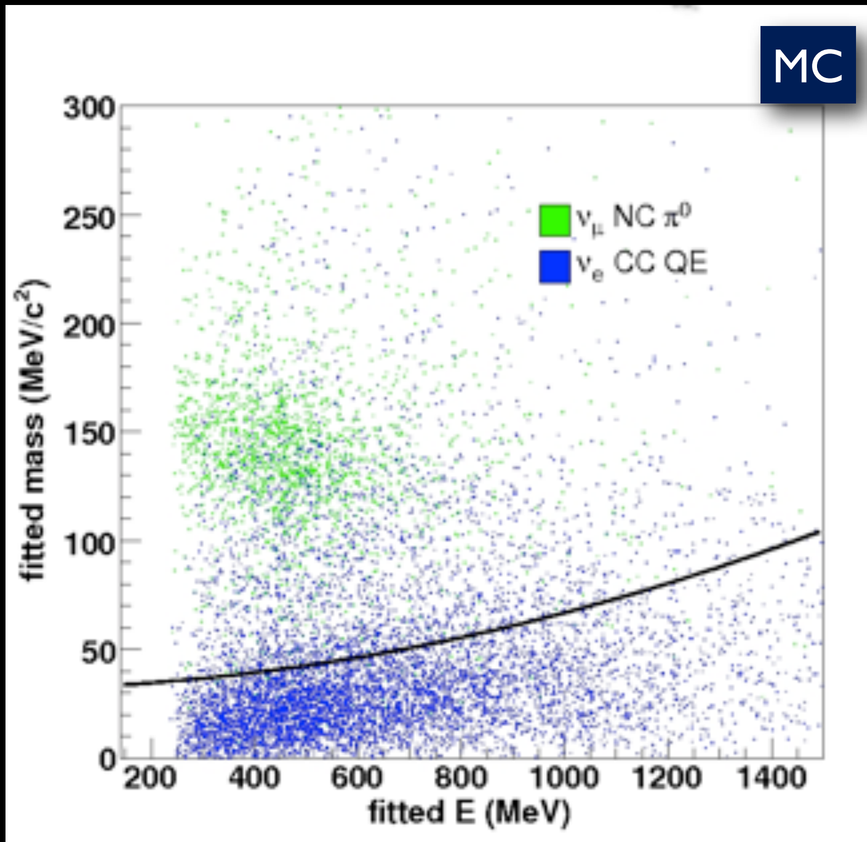


- 12m sphere filled with 800t of undoped mineral oil
- 1280 PMTs in inner region (10% coverage), 240 PMTs in veto region
- Neutrino interactions in oil produce Cherenkov and scintillation light

☑ Powerful neutrino flavor tagging (ν_μ .vs. ν_e interaction)





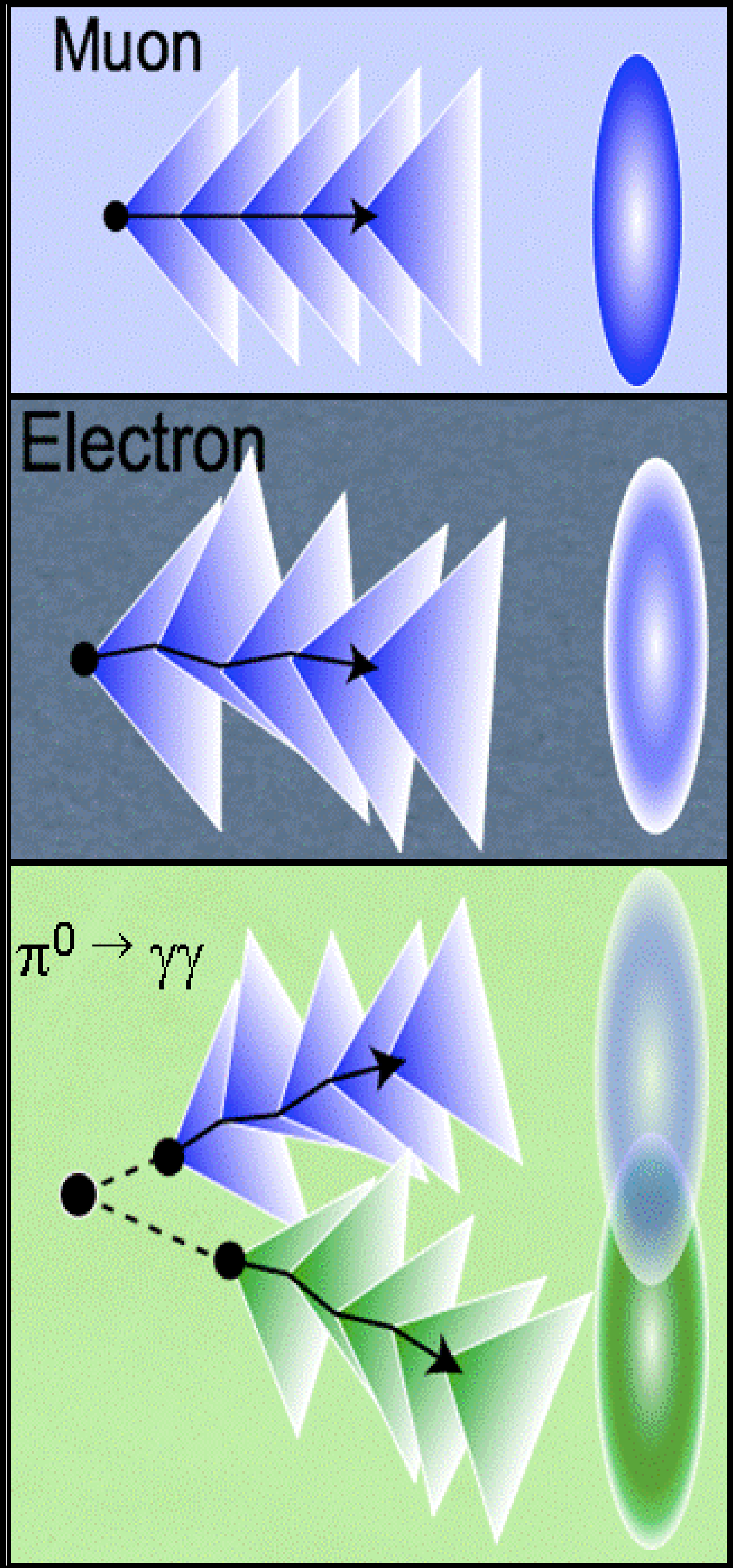


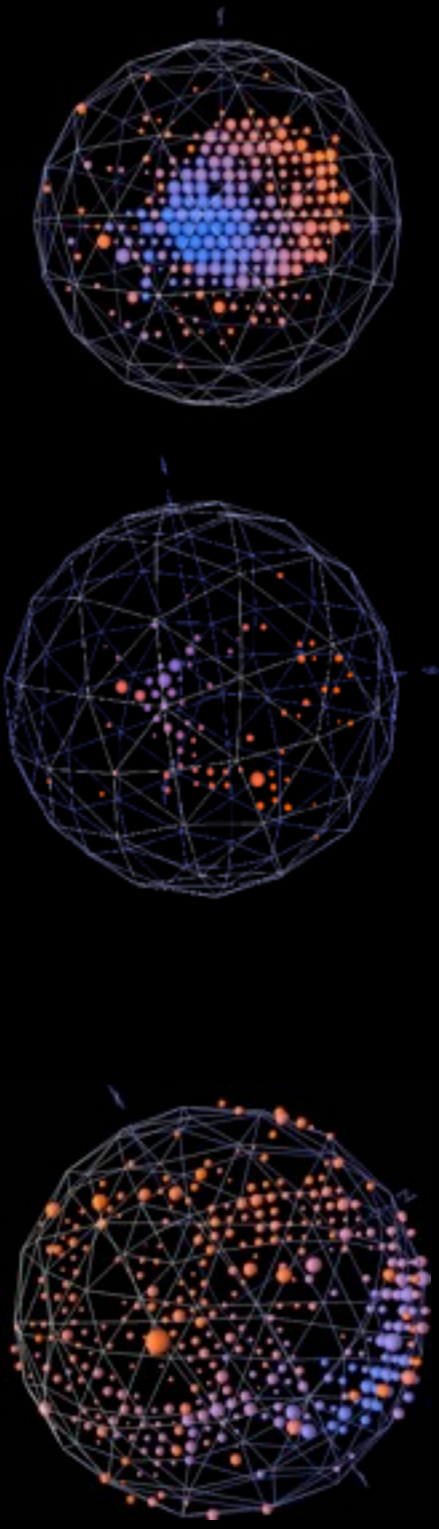
Powerful neutrino flavor tagging (ν_μ .vs. ν_e interaction)

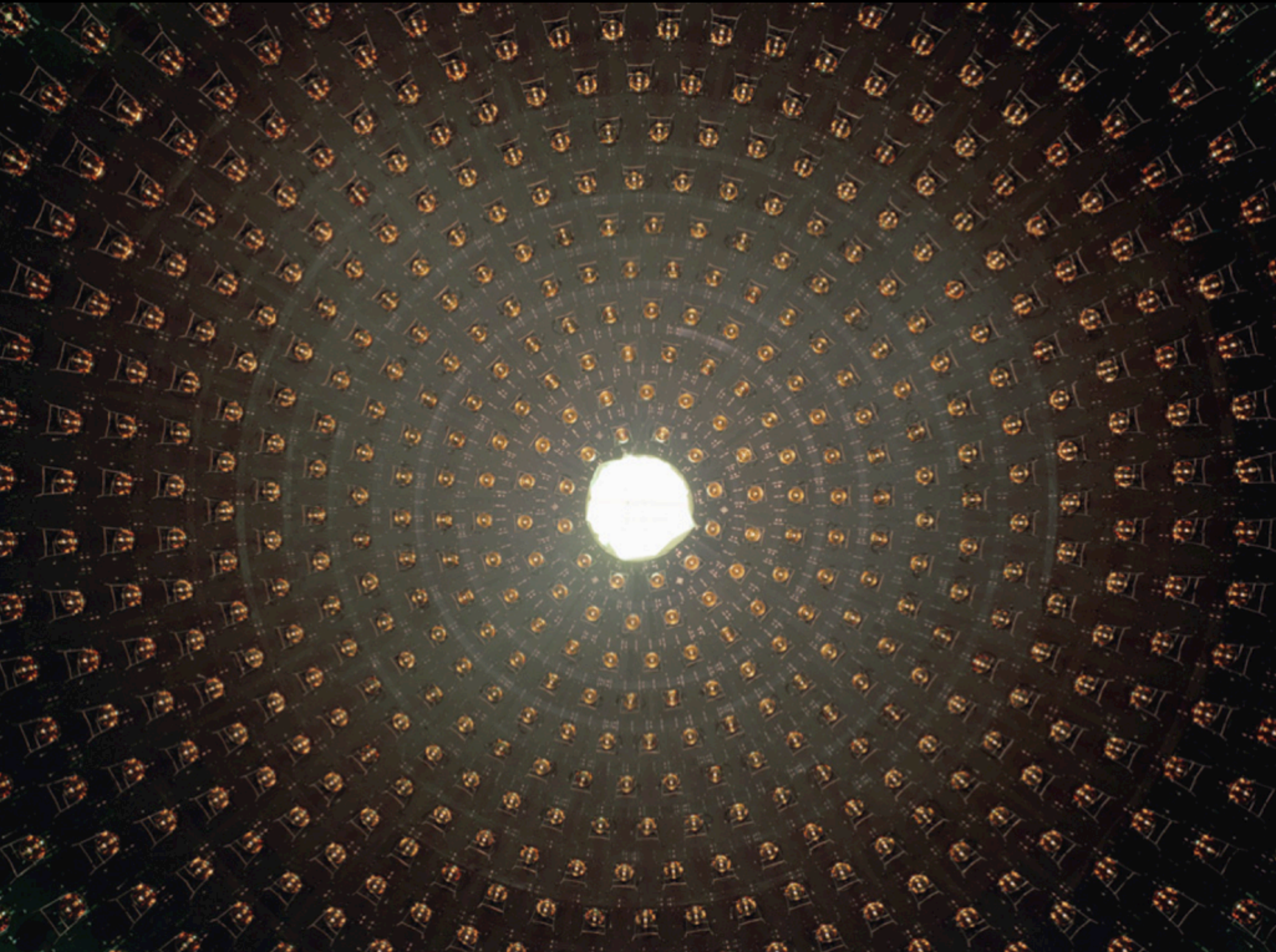
Muons:
- long tracks
- sharp Cherenkov ring
- ~80% with decay electron tag

Electrons:
- short tracks
- fuzzy Cherenkov ring
- single subevent

$\pi^0 \rightarrow \gamma\gamma$:
- disconnected short tracks
- typically two fuzzy rings with $m_{\gamma\gamma} \sim m_\pi$
- single subevent



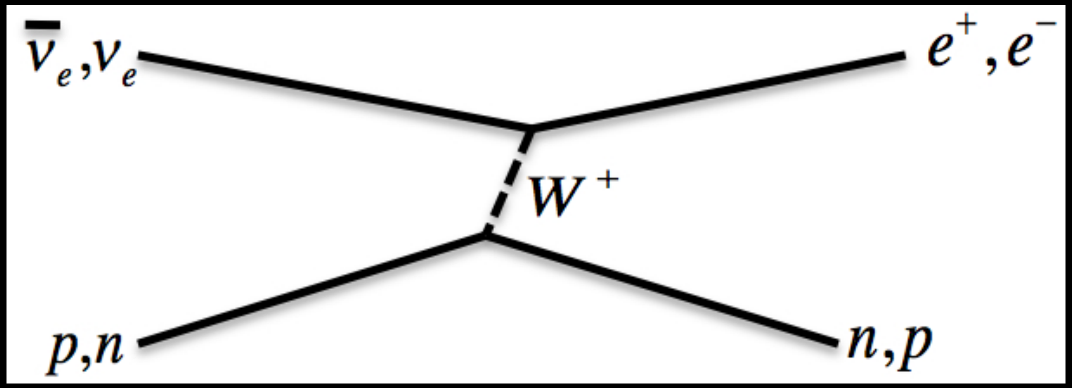




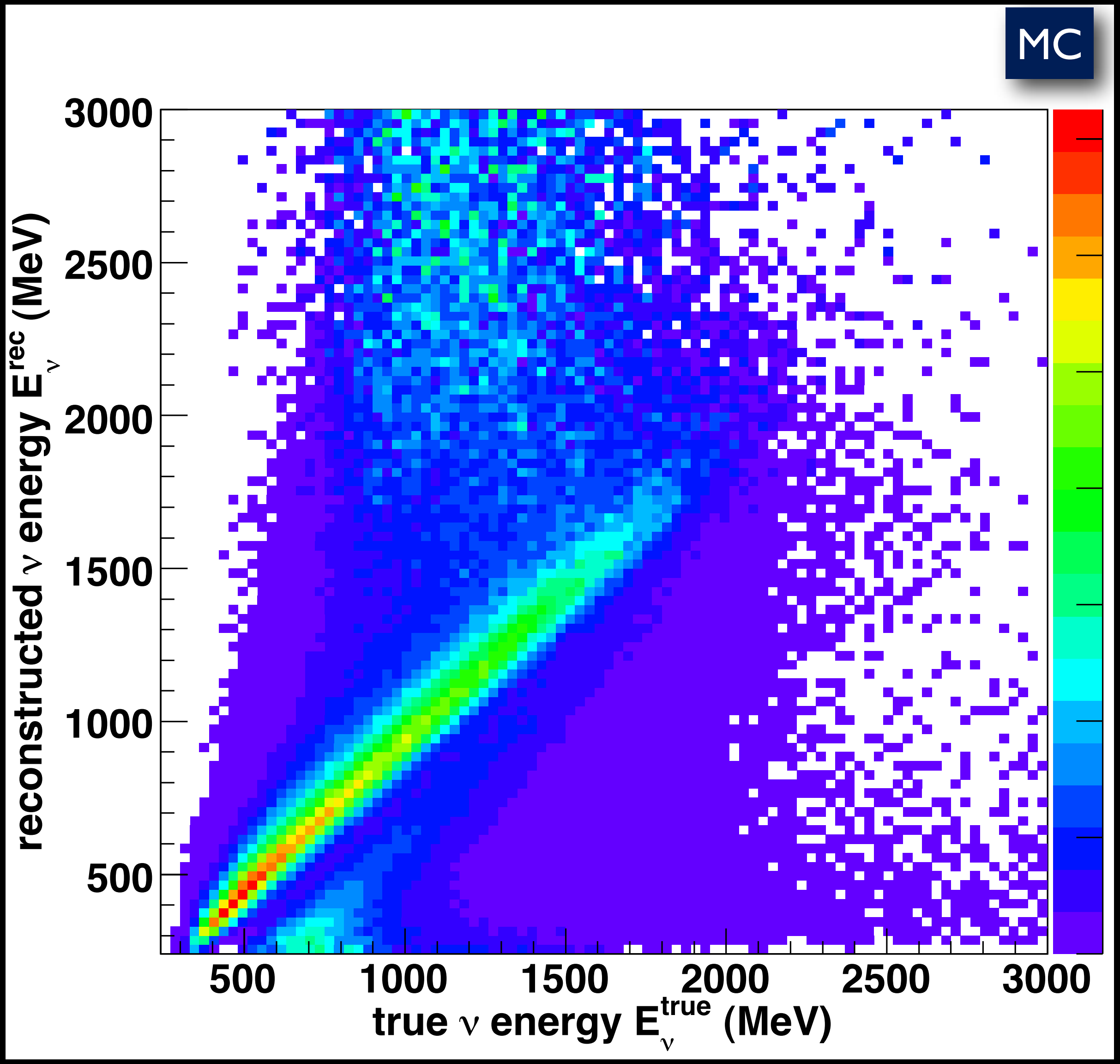
☑ Information about neutrino energy spectrum

- Reconstruct final state electron kinematics from Cherenkov light yield and pattern

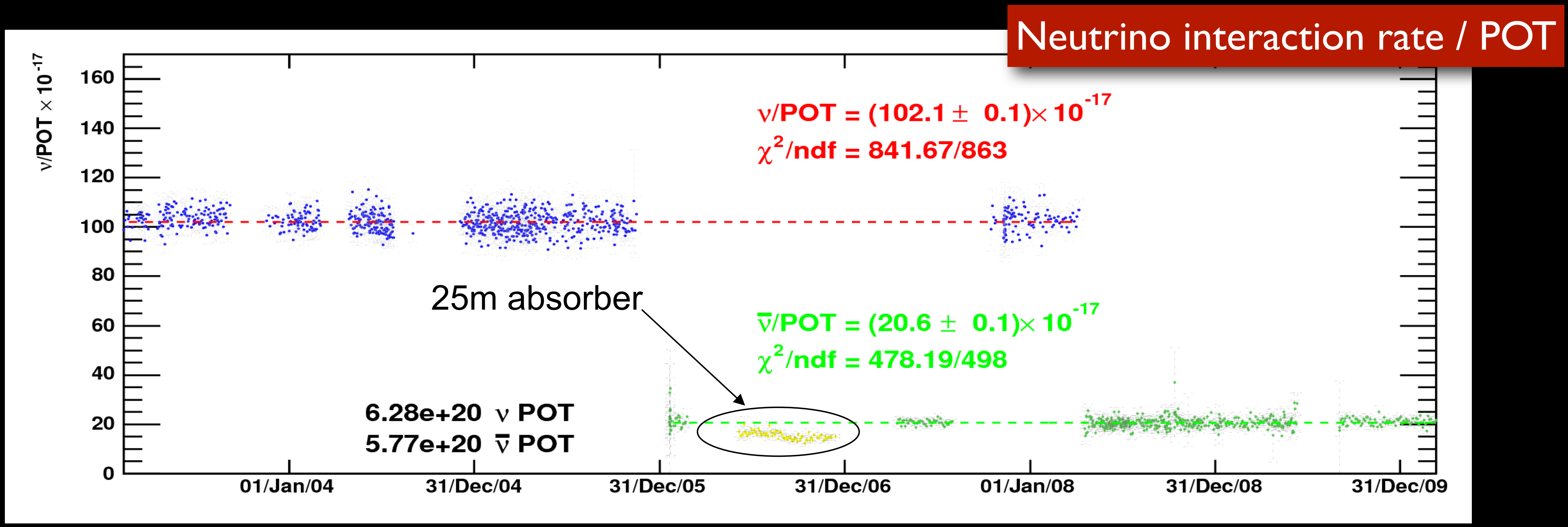
- Reconstruct neutrino energy from electron kinematics and assuming QE interaction:

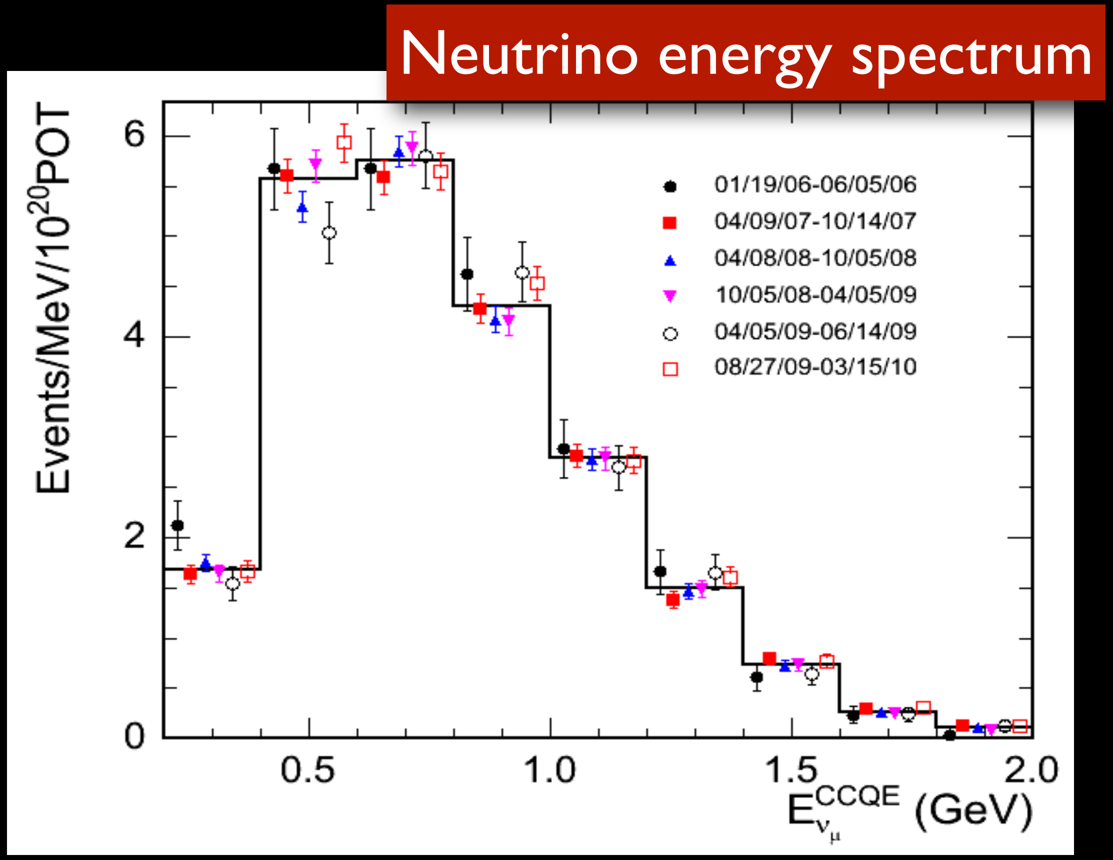


- 11% energy resolution for ν_e events



☑ Patience (& data stability)





- Beam and detector performance very stable over many years
- Thanks to the dedication of many people

MiniBooNE $\nu_\mu \rightarrow \nu_e$

(Known) Backgrounds

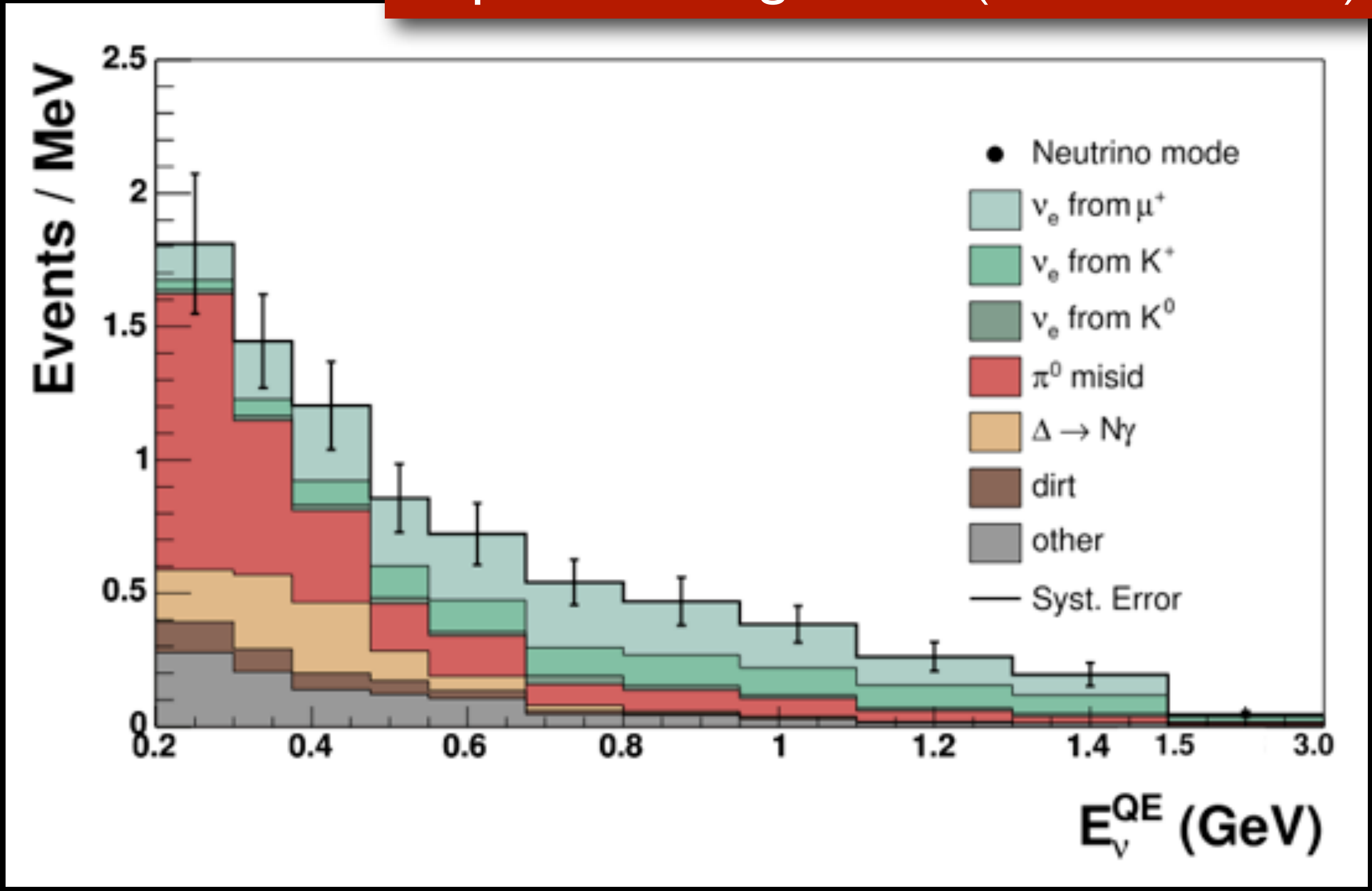
High energy: intrinsic ν_e

- From $\pi \rightarrow \mu$
  - HARP p-Be π^+ production data
  - MiniBooNE ν_μ CCQE rate .vs. E_ν
- From K
  - External p-Be K production data
  - New: SciBooNE high-energy ν_μ

Low energy: mis-identified ν_μ

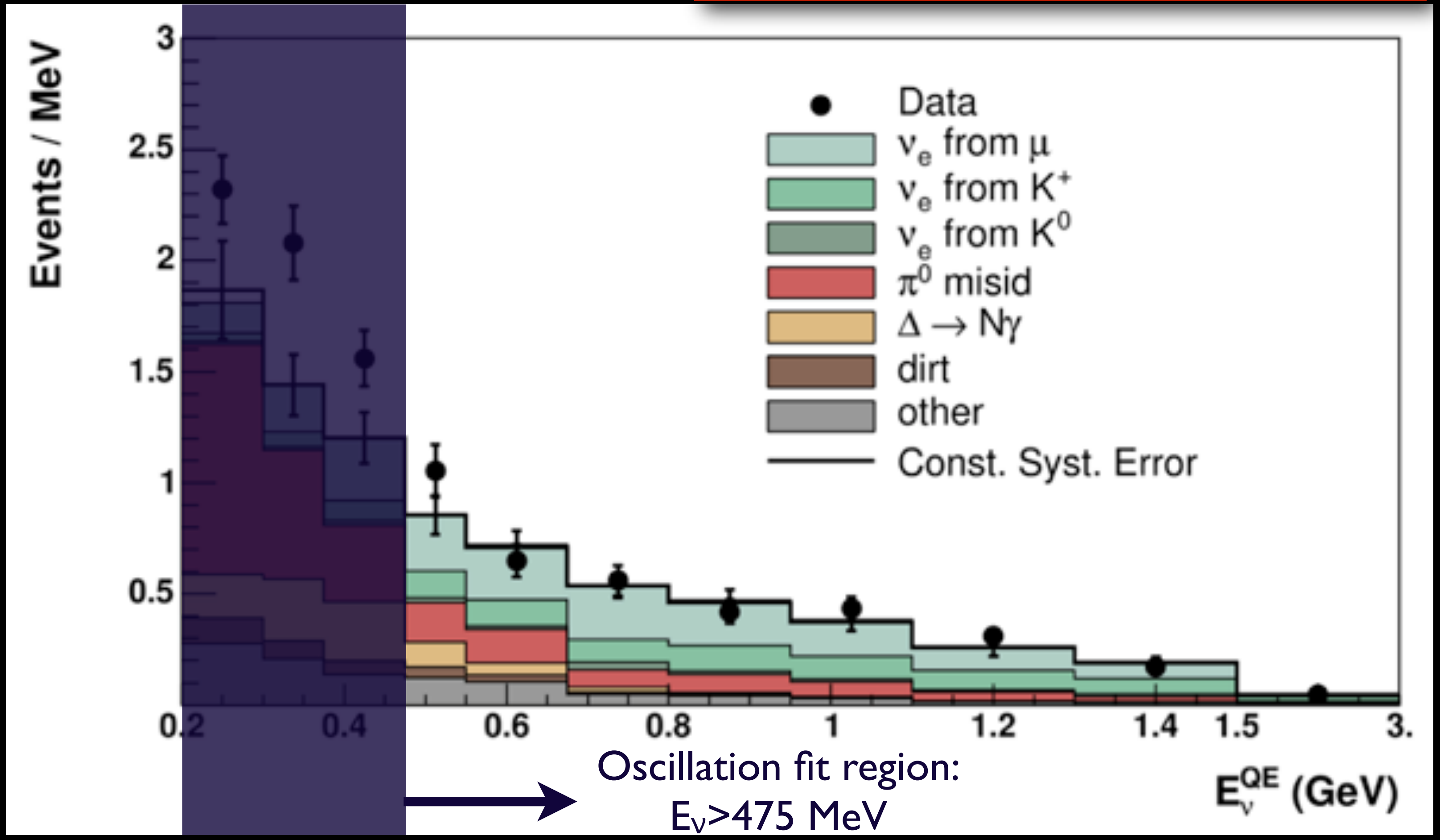
- NC π^0
  - MiniBooNE clean NC π^0 rate .vs. p_π
- NC followed by Δ radiative decay
  - MiniBooNE NC π^0 times BR
- Interactions outside detector ("dirt")
  - MiniBooNE dirt rate measurement

Expected backgrounds ($6.46 \cdot 10^{20}$ POT)



Results (Oscillation Fit Region)

PRL 102, 101802 (2009), $6.46 \cdot 10^{20}$ POT



$475 < E_\nu < 1250$ MeV counts:

- 22.1 ± 35.7 excess events
- No evidence for oscillations

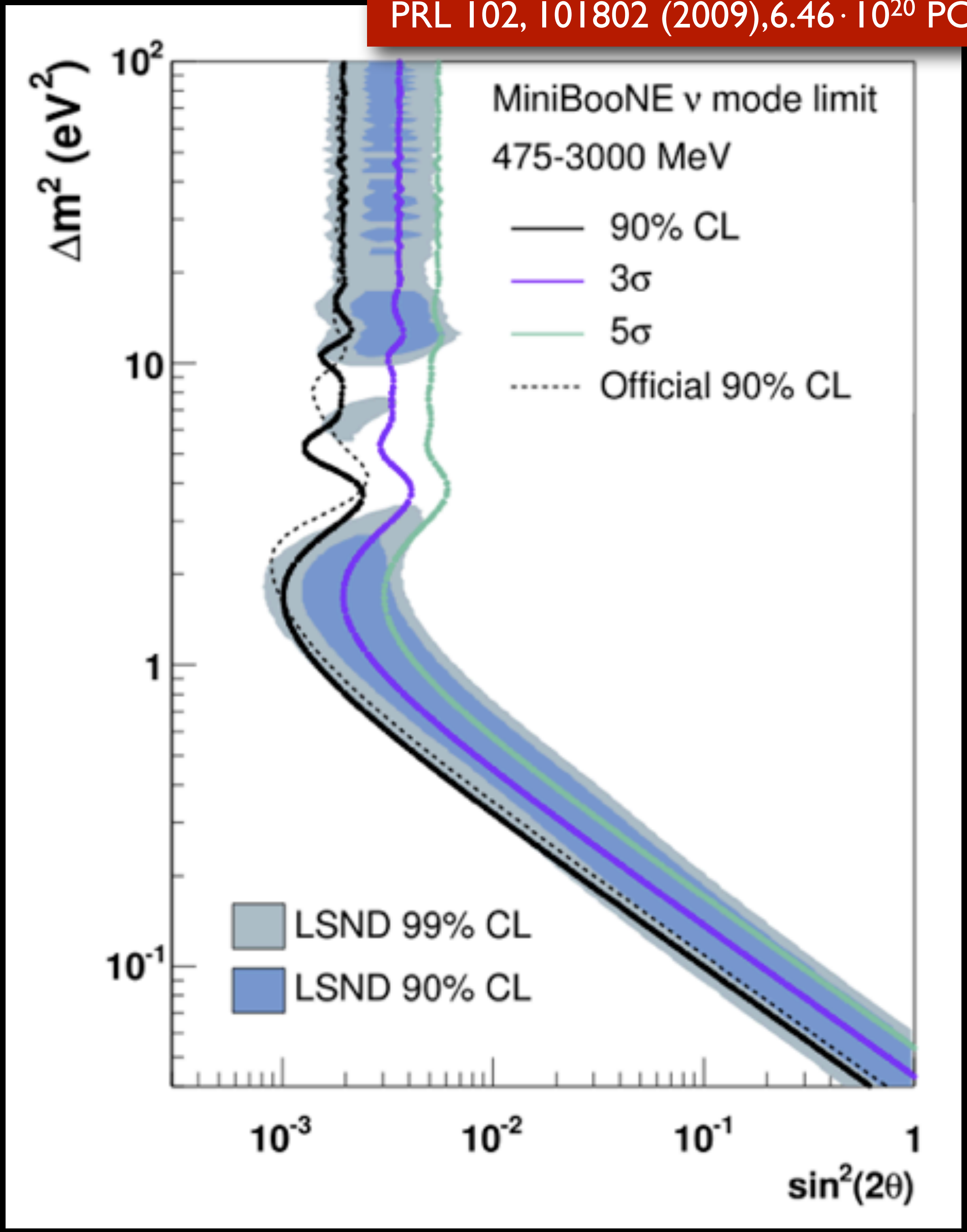
$E_\nu > 475$ MeV energy fit:

- null: χ^2/dof = 9.1/15 (87%)
- best-fit: χ^2/dof = 7.2/13 (89%)

- Assume no ν_μ/ν_e disappearance

Results (Oscillation Fit Region)

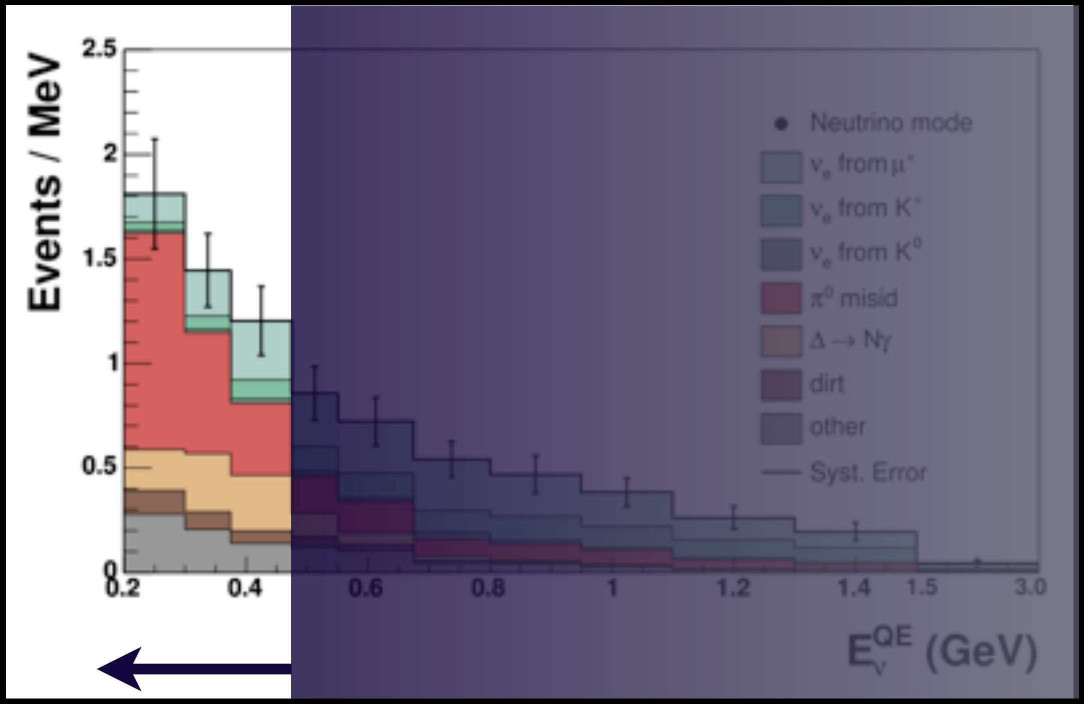
PRL 102, 101802 (2009),6.46$\cdot 10^{20}$ POT

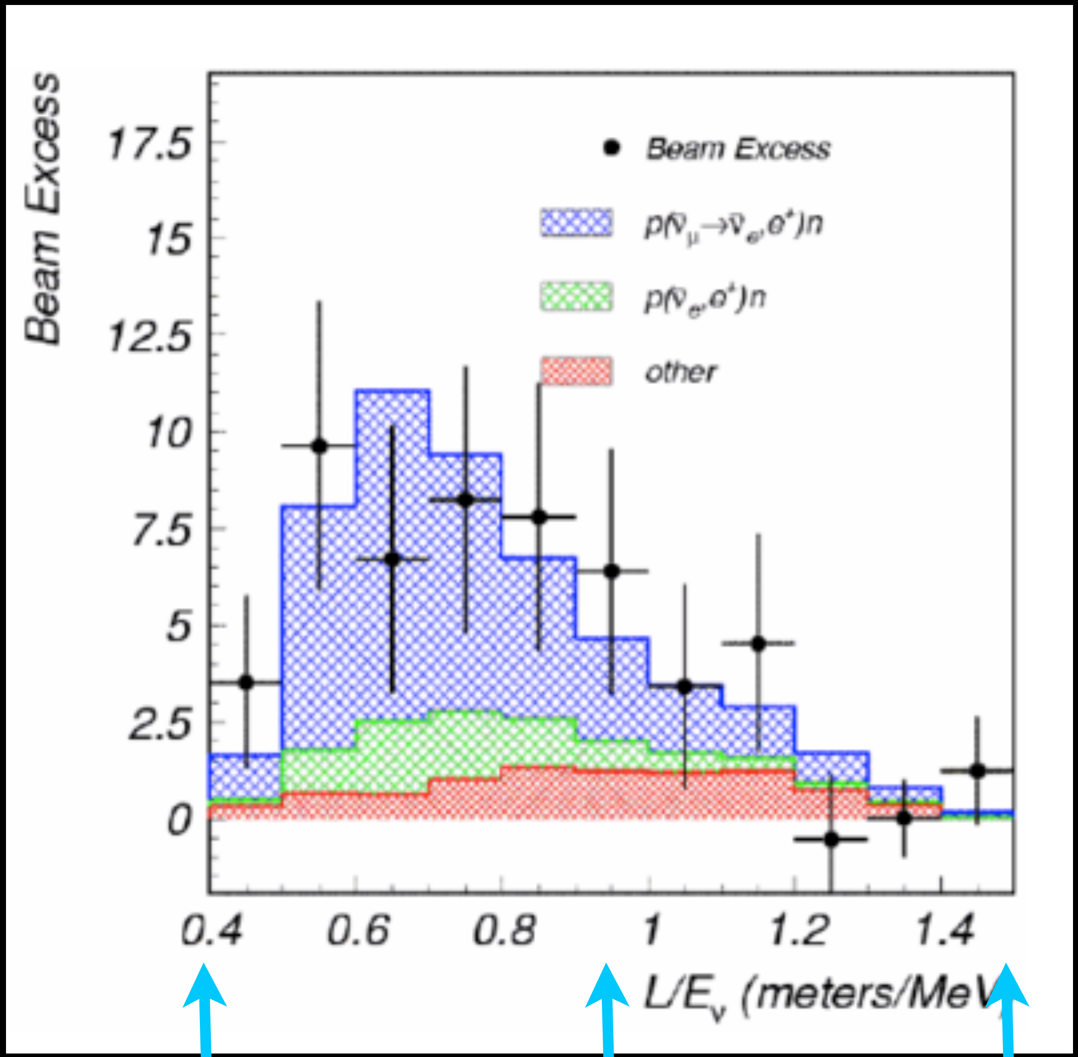


- **MiniBooNE rules out the LSND two-neutrino oscillation interpretation (assuming no CP or CPT violation)**

Results (Low Energies)

- Excluded from oscillation fit as part of unblinding procedure
  - Larger backgrounds, harder to model
  - Does not affect sensitivity to LSND oscillations



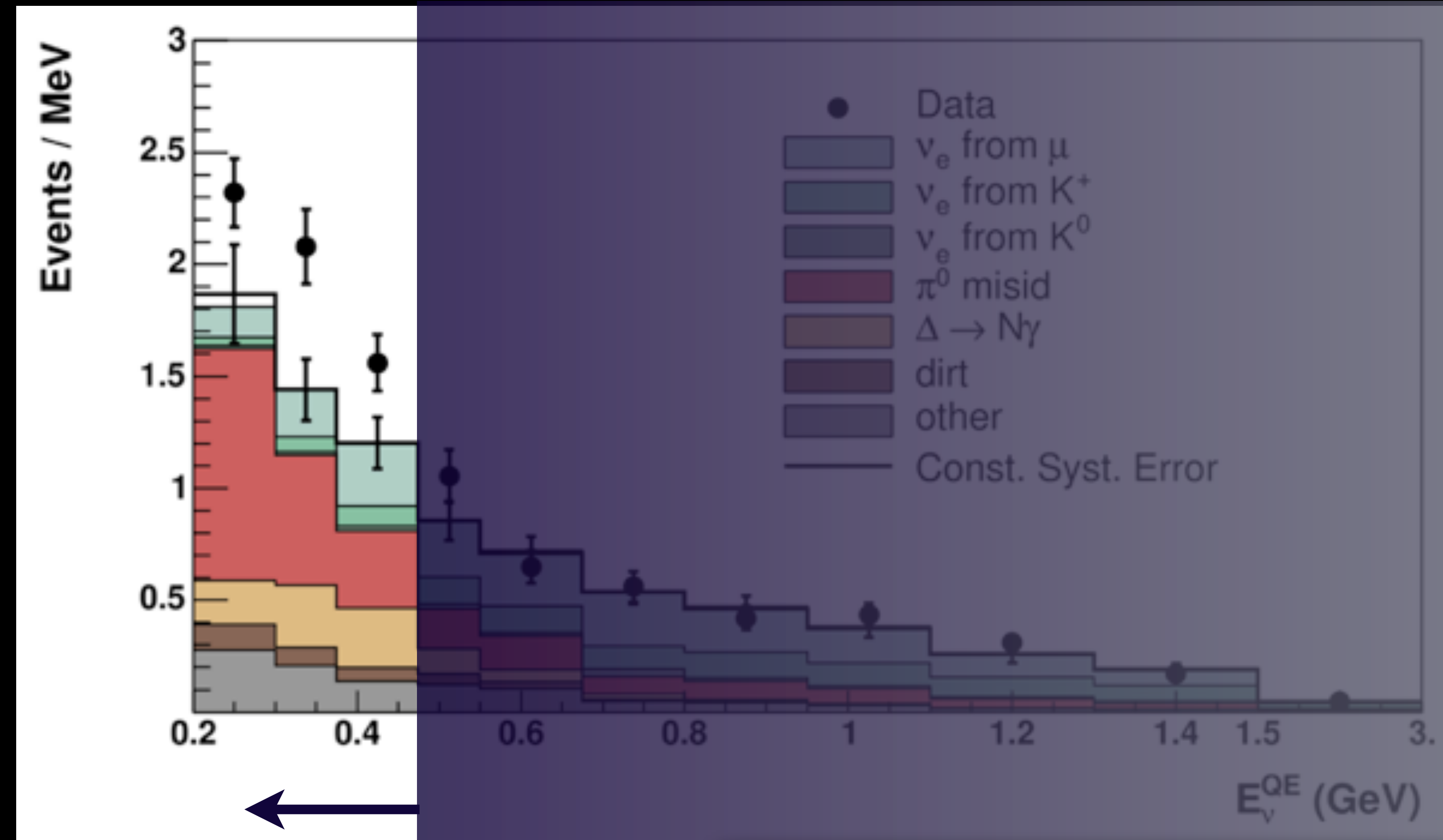


1250 475 333

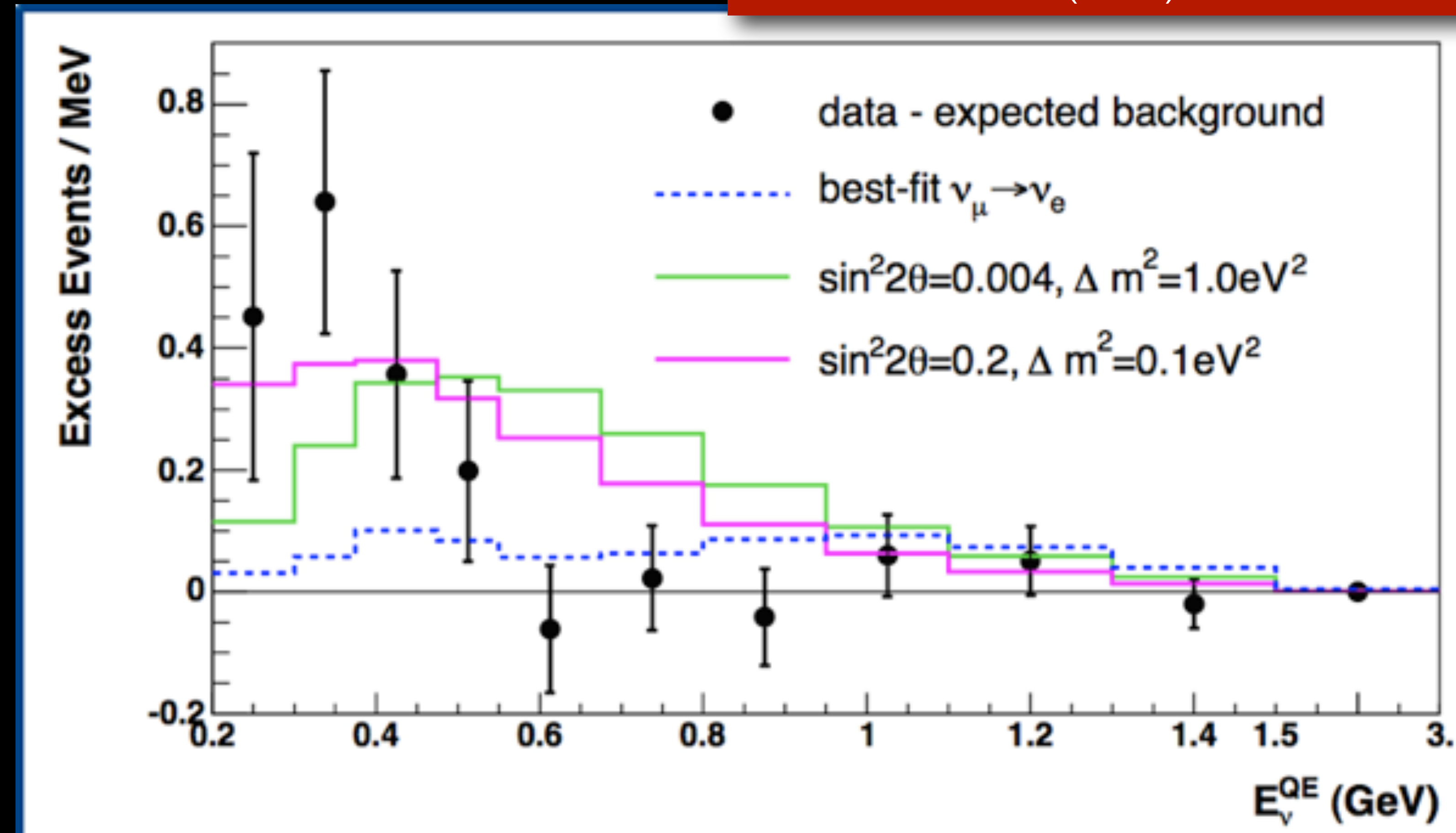
Energy in MiniBooNE (MeV)

Results (Low Energies)

- 200 < E_ν < 475 MeV counts:
  - 128.8 ± 20.4 ± 38.3 excess events
  - 3.0σ significance
- Shape inconsistent with 2ν oscillations
- Excess remains unexplained

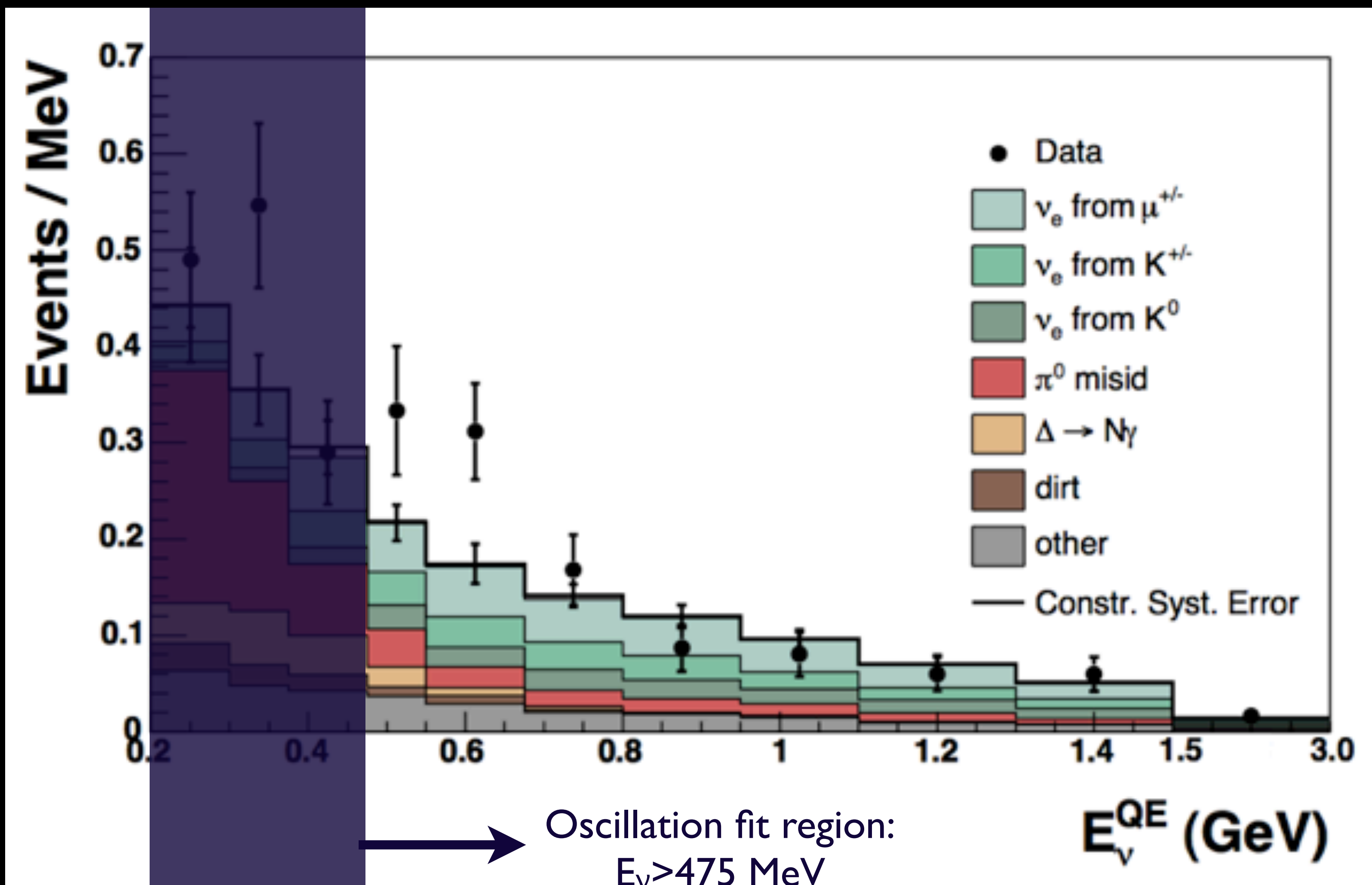


PRL 102, 101802 (2009), $6.46 \cdot 10^{20}$ POT



MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Results



475 < E_ν < 1250 MeV:

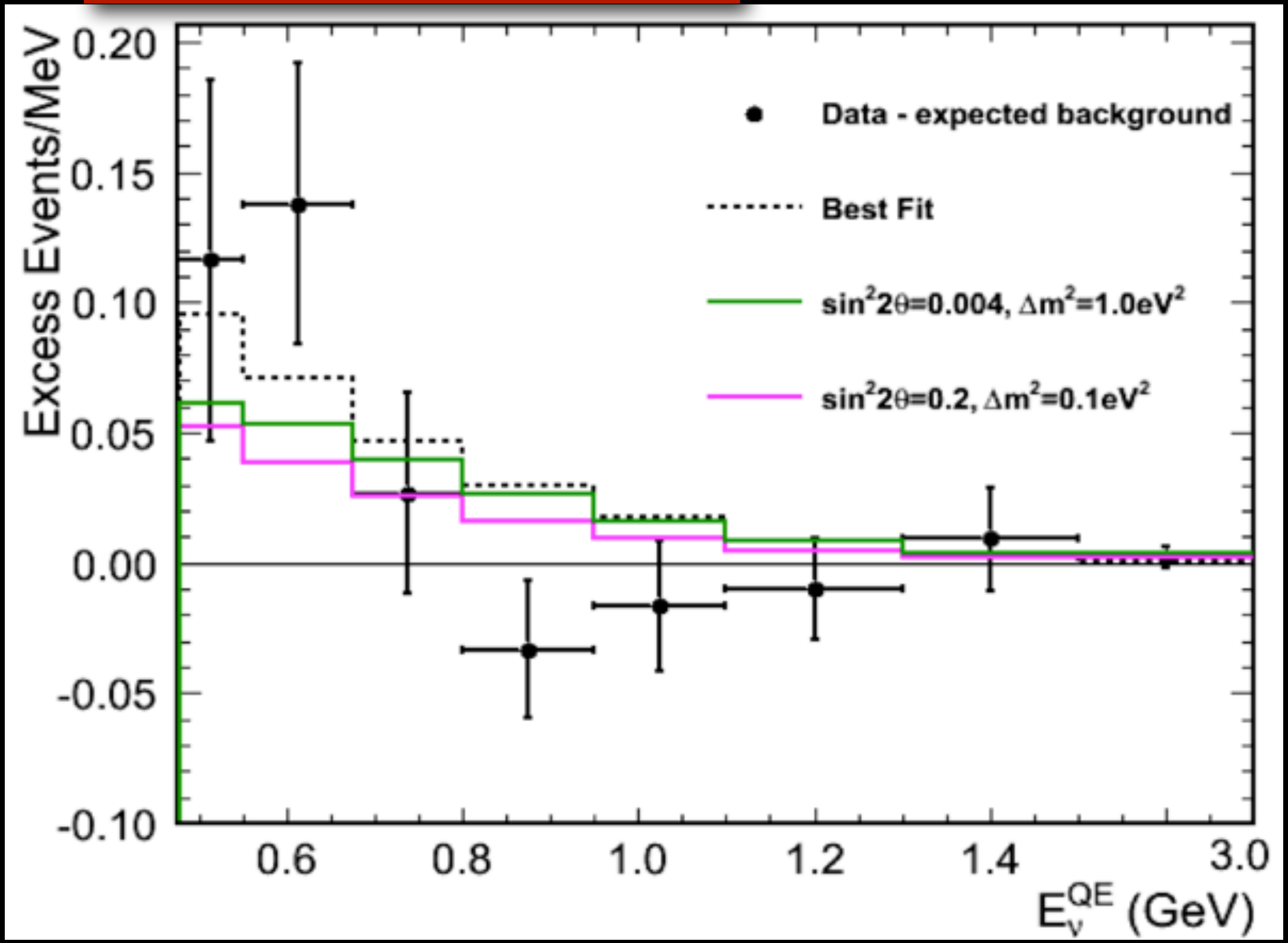
- 20.9 ± 14.0 excess events
- Consistent with LSND best fit expectation: 22 events

- Significance of excess largely in energy shape different from bgr:
  - null: χ^2/dof = 18.5/6
  - 0.5% probability for background-only hypothesis

PRL 105, 181801 (2010), $5.66 \cdot 10^{20}$ POT

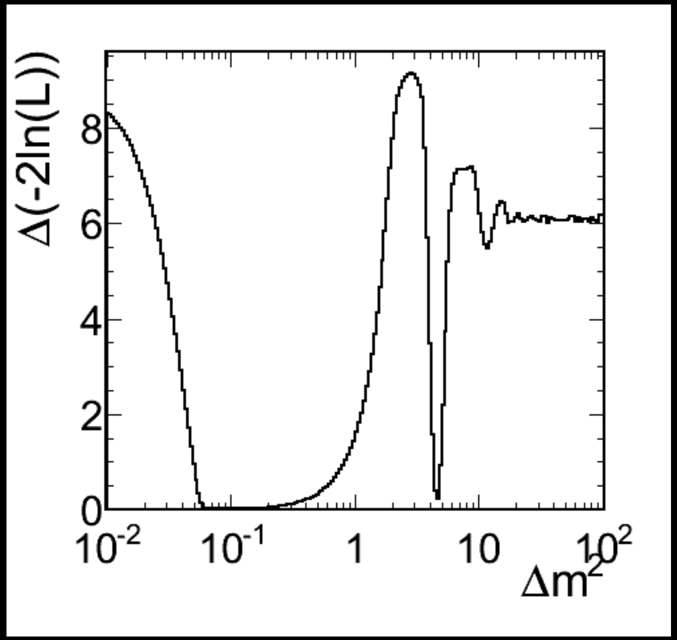
Results

PRL 105, 181801 (2010), $5.66 \cdot 10^{20}$ POT



E-dependent fit to oscillations:

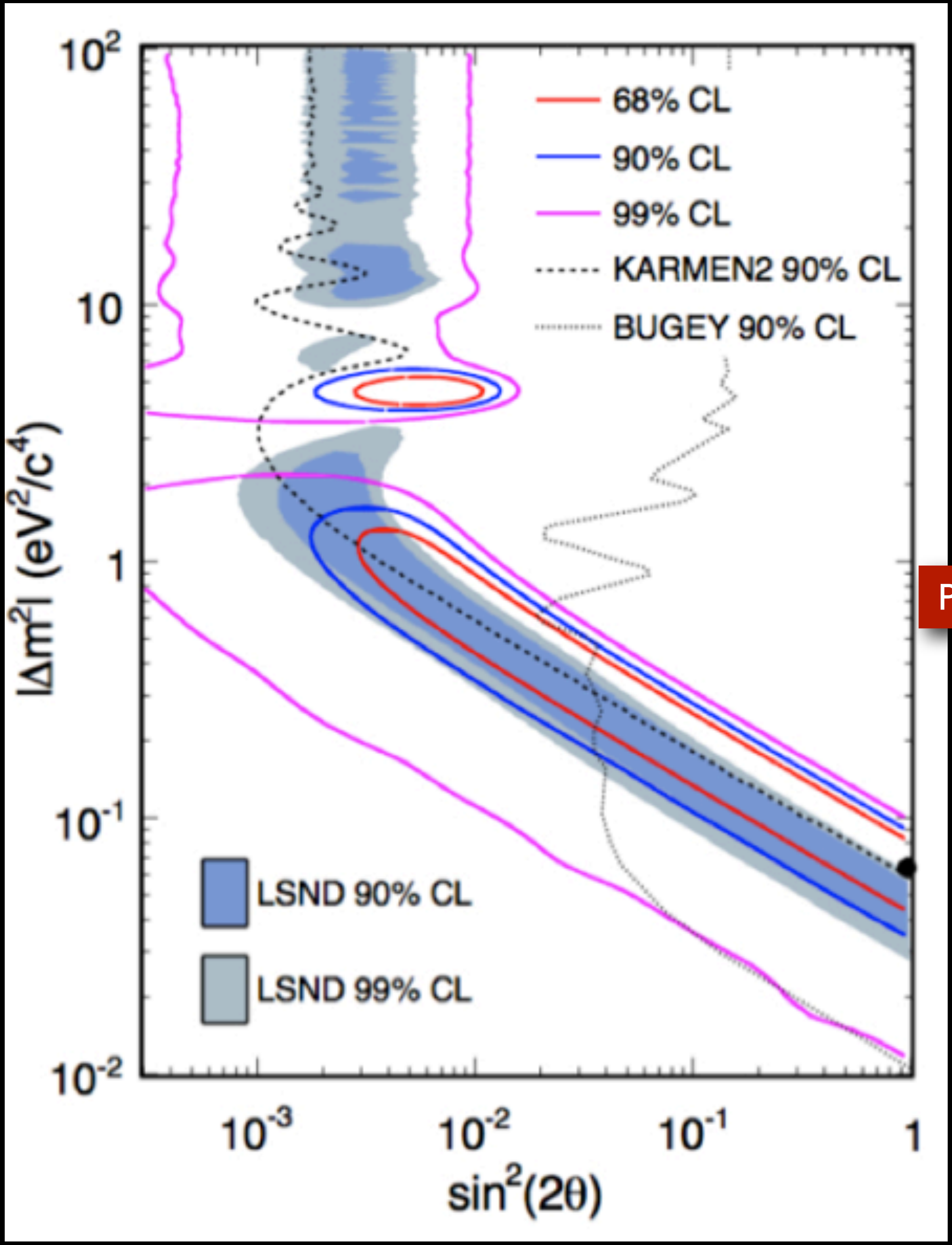
- Assume no ν_μ/ν_e disappearance
- Assume only antineutrinos oscillate
- Best fit: $(\sin^2 2\theta, \Delta m^2) = (0.96, 0.064\ \mathrm{eV}^2)$



$475 < E_\nu < 1250$ MeV:

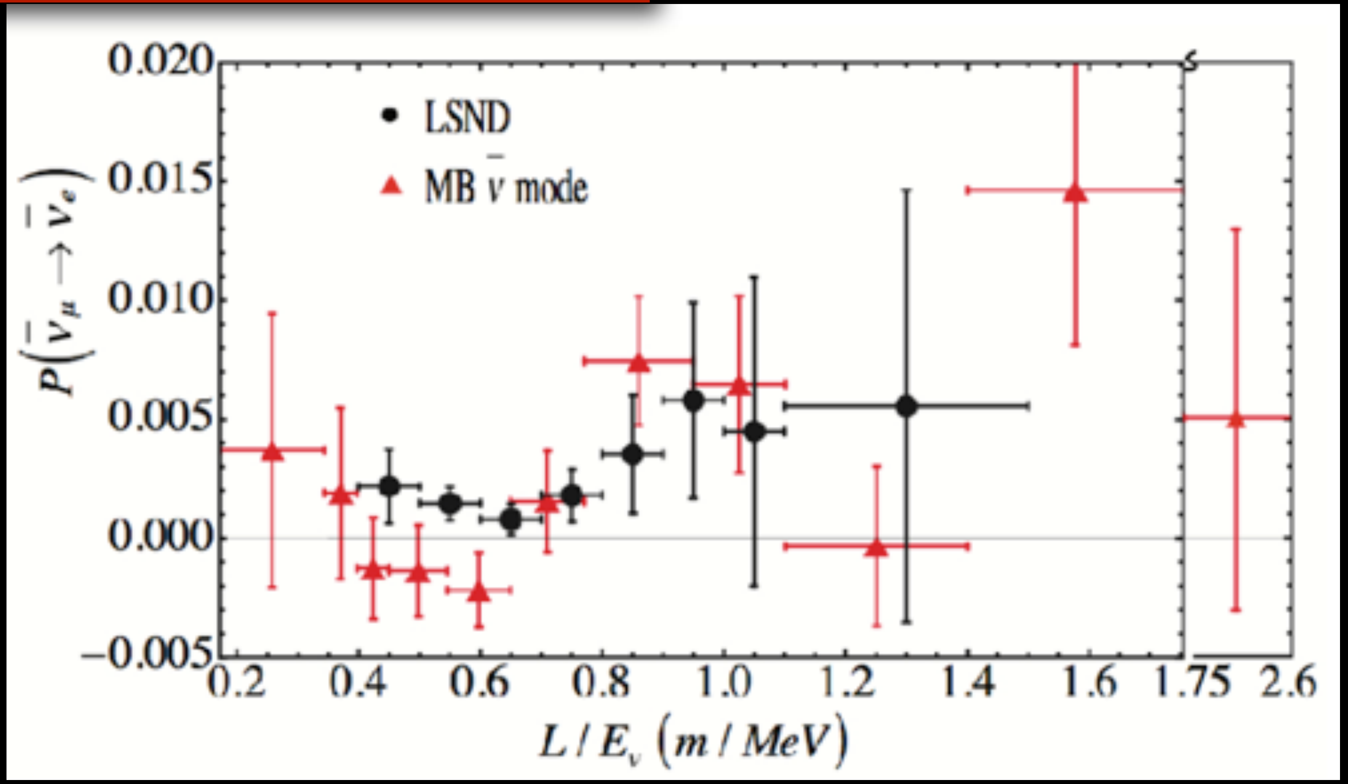
- Best fit: χ^2/dof = 8.0/4 (8.7%)
- Consistent with 2ν oscillations
- Oscillations favored over background hypothesis at 99.4% CL

Results

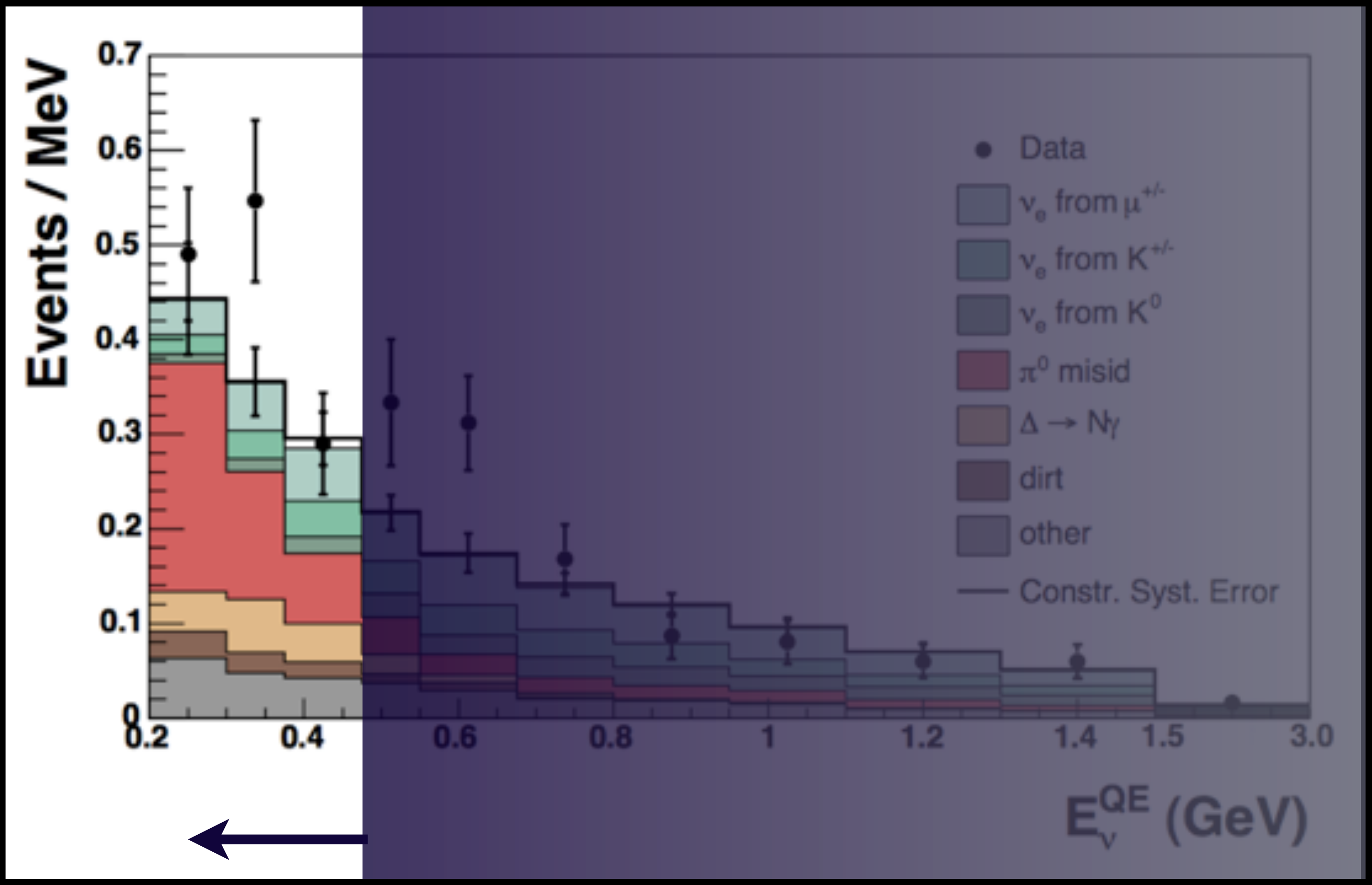


- Consistent with oscillation interpretation of LSND
  - Overlap in oscillation parameters allowed regions
  - Consistent L/E trend for excess-inferred oscillation probabilities

PRL 105, 181801 (2010), $5.66 \cdot 10^{20}$ POT



What About the Low Energy Region?



	200-475 MeV
Data	119
MC	100.5 ± 14.3
Excess	18.5 ± 14.3
LSND Best Fit	7.6
Expectation from ν low E excess	11.6
LSND + Low E	19.2

- Assuming only neutrinos in the beam contribute to the excess, scaling from ν mode

Confused? Here's a Summary of MiniBooNE Appearance Claims

1. In a ν_μ beam above 475 MeV, we see no evidence for an excess of ν_e-like events

2. In a ν_μ beam below 475 MeV, we see a 3σ excess (128 + 43) of ν_e-like events that does not fit well a 2ν oscillation hypothesis

3. In a $\bar{\nu}_\mu$ beam below 475 MeV, we see (18 ± 14) events, consistent with both no excess and LSND + ν-only low-E excess. This rules out some explanations of the ν_μ beam low-E excess

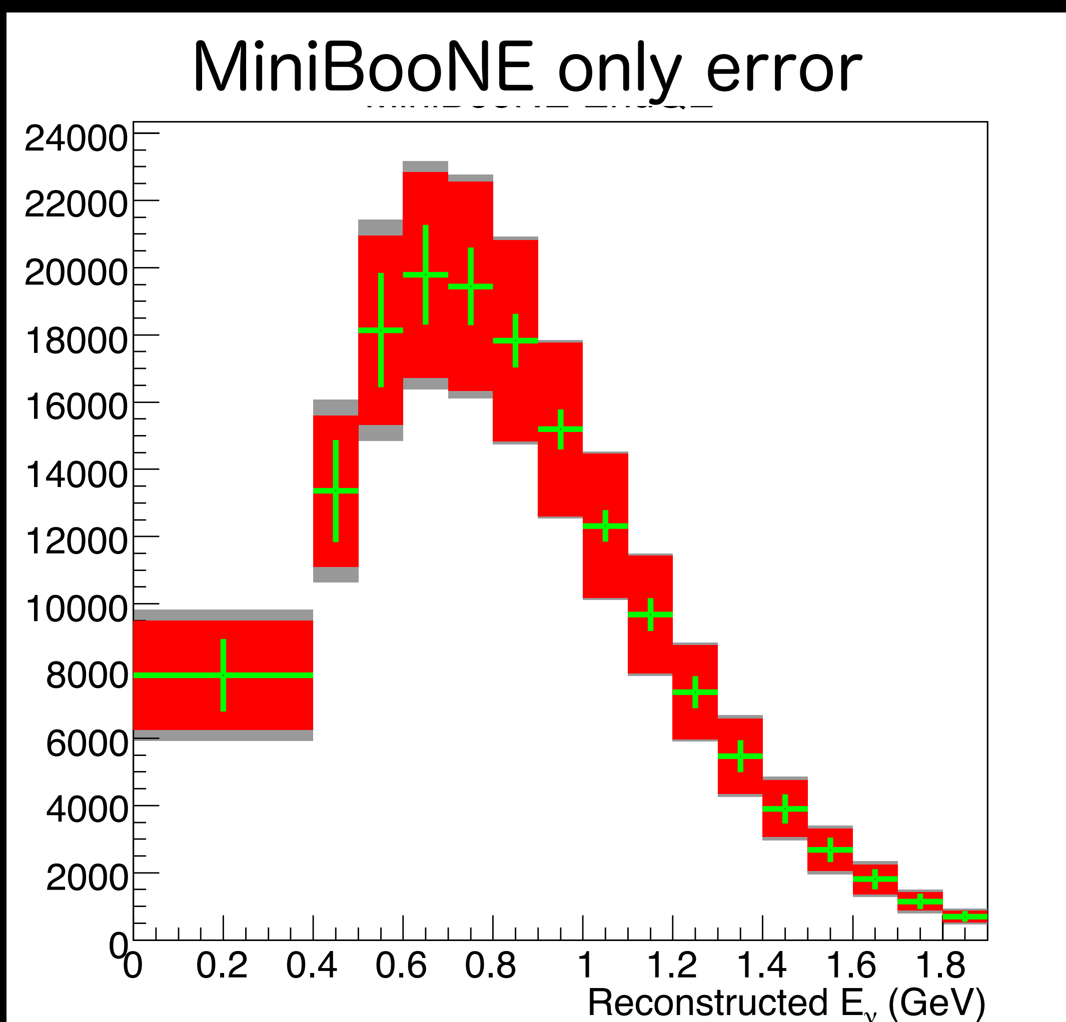
4. In a $\bar{\nu}_\mu$ beam above 475 MeV, we see an excess of events. The null hypothesis in the 475-1250 MeV region is only 0.5% probable. A 2ν fit prefers an LSND-like signal at 99.4% CL

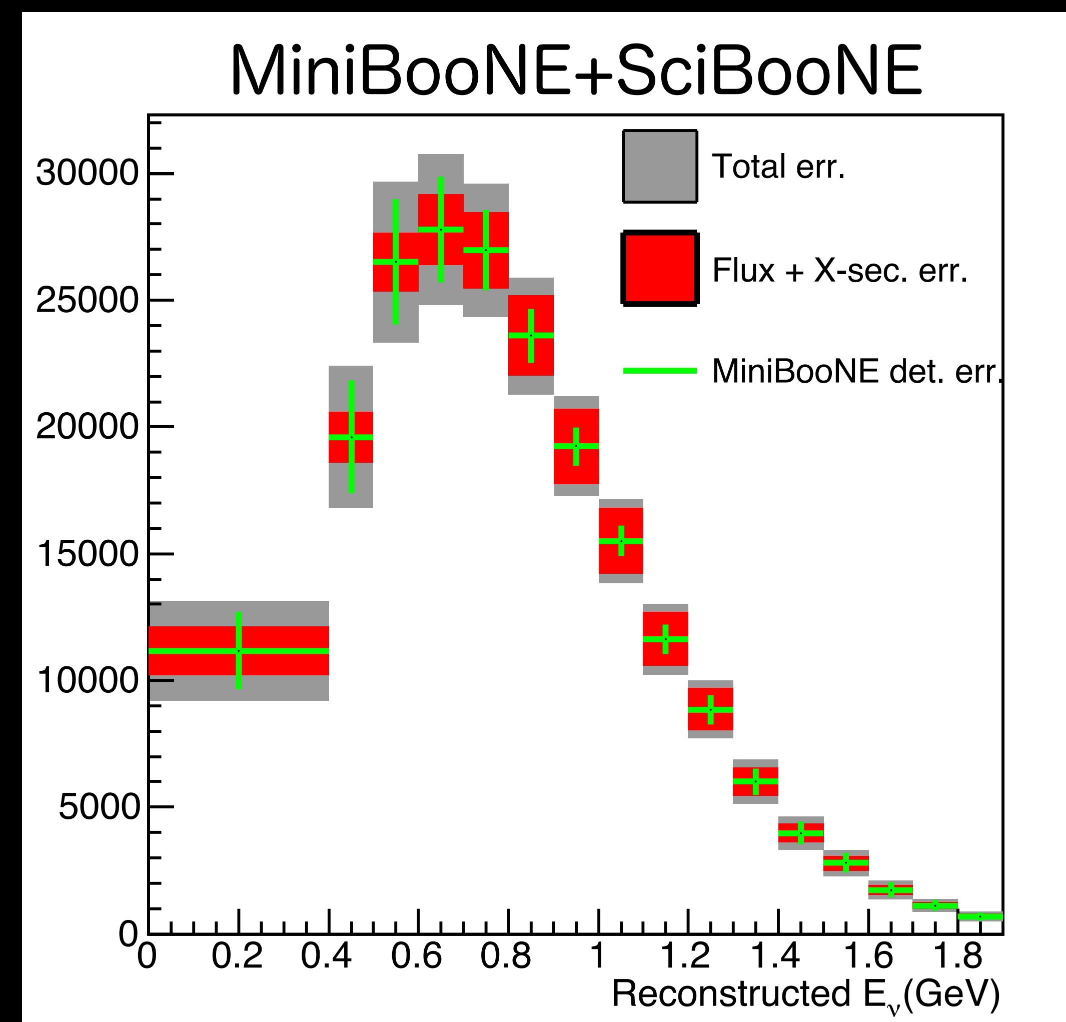
MiniBooNE $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

New SciBooNE+MiniBooNE Results

- SciBooNE: near detector in same beam as MiniBooNE, 100m from production target

- SciBooNE ν_μ data allow to reduce flux and cross section systematic uncertainties affecting MiniBooNE ν_μ predictions to same level as detector response uncertainties:





Improvement over MiniBooNE-only analysis (2009)

New SciBooNE+MiniBooNE Results

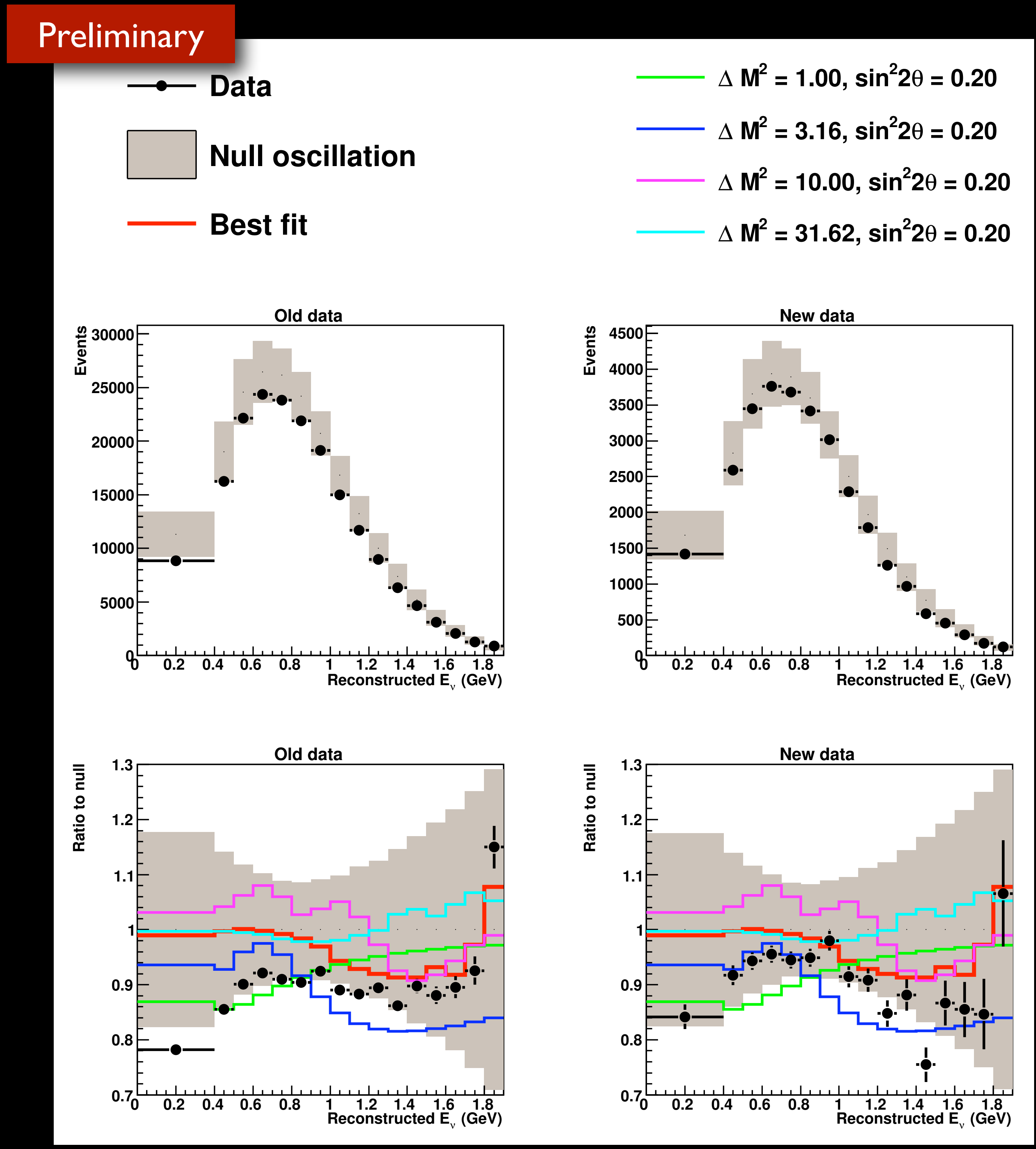
- Use MiniBooNE neutrino mode data taken both prior to ("old") and together with ("new") SciBooNE

- Best fit: Δm^2=42 eV^2, $\sin^2 2\theta$=0.51

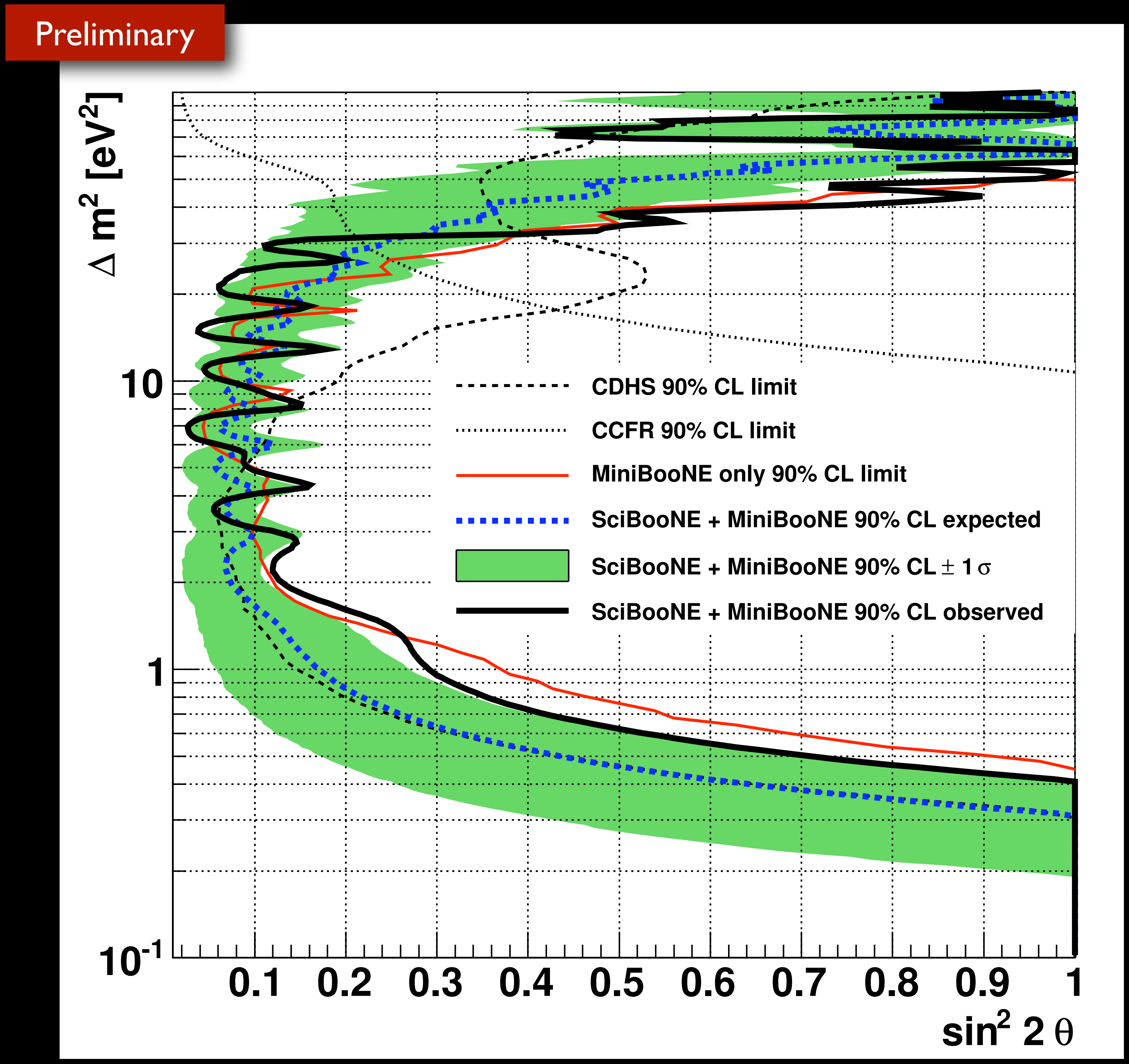
- Null: χ^2/dof = 41.5/32
- Best: χ^2/dof = 35.6/30

- $\Delta\chi^2$(observed)=5.9
- Simulations: $\Delta\chi^2$(90% CL, null)=8.4

- **No significant ν_μ disappearance observed**



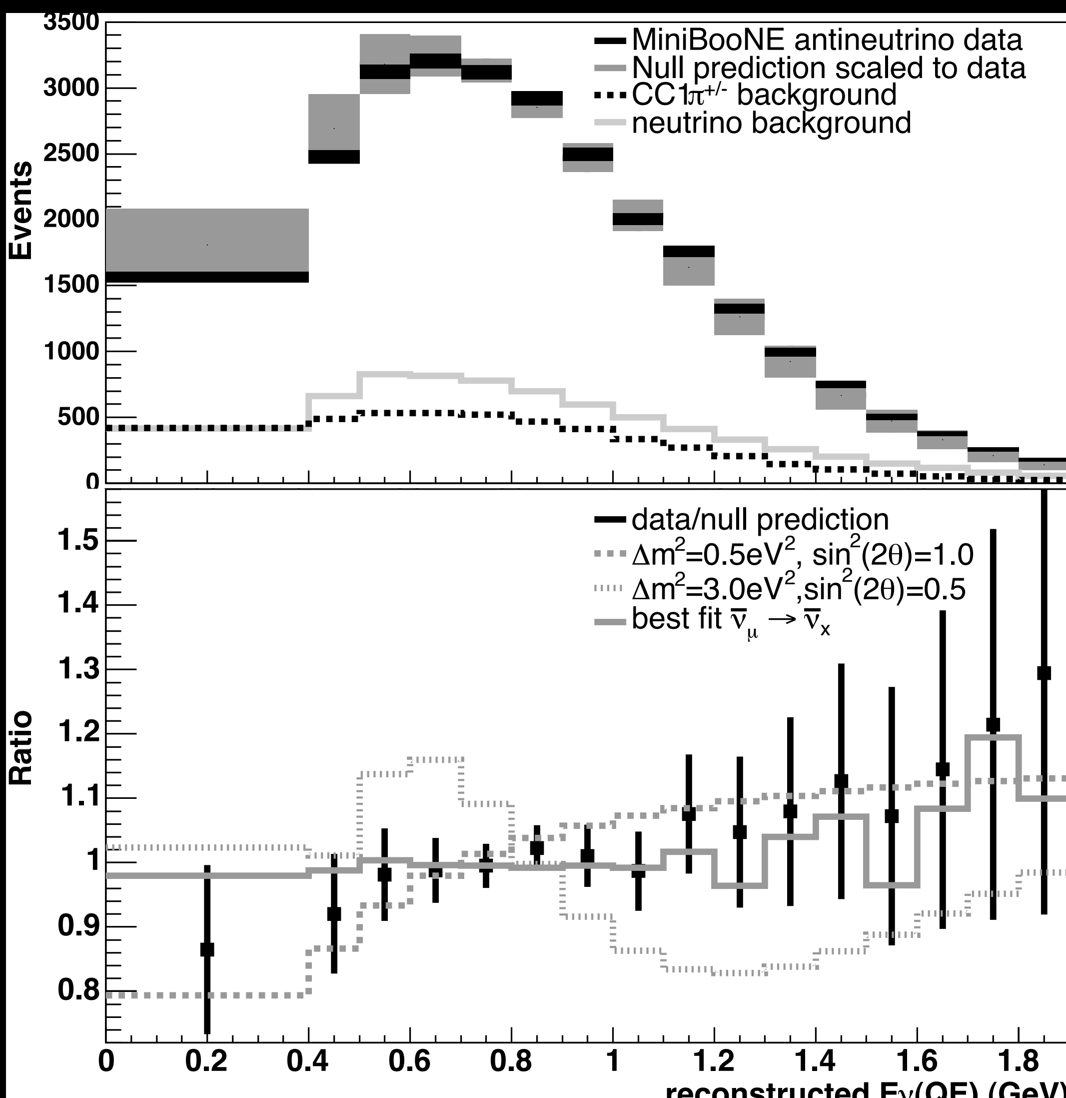
New SciBooNE+MiniBooNE Results

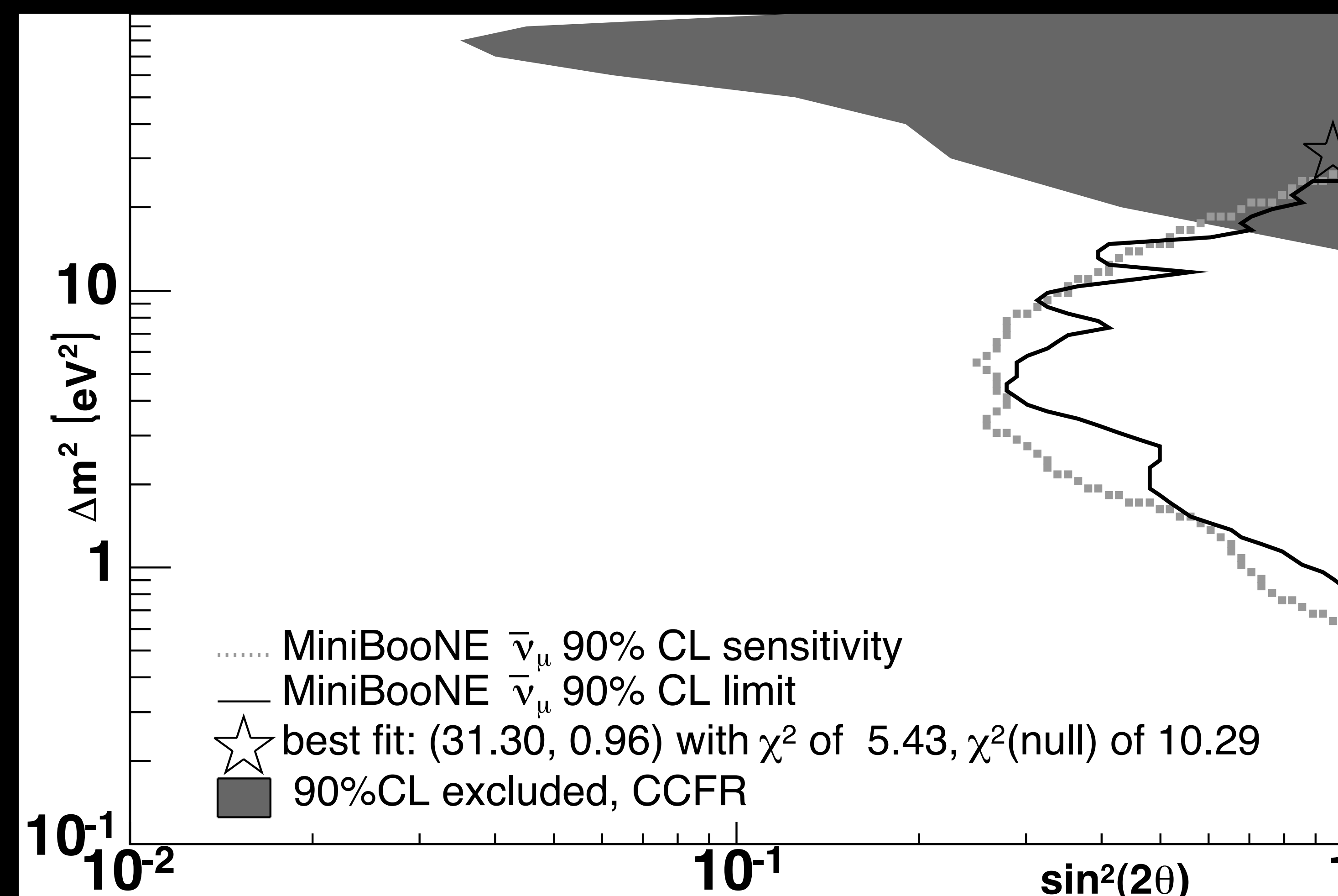


- World's strongest limit for $10 < \Delta m^2 < 30$ eV^2
- Limit weaker than sensitivity for $\Delta m^2 < 30$ eV^2 because of small data deficit observed
- Constrains sterile neutrino mixing models

MiniBooNE $\bar{\nu}_\mu$ Disappearance

- 2009 results: no $\bar{\nu}_\mu$ disappearance observed, but limited sensitivity
- Current antineutrino mode data statistics (x3 2009 result) + SciBooNE near detector constraint will allow for a more sensitive search
- Particularly interesting now, given MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results!





PRL 103, 061802 (2009)

Light sterile neutrino oscillations: where we stand

Some Personal Comments

- Three talks to follow on sterile neutrino phenomenology, certainly with more details...
- Only some personal comments, based on work with G. Karagiorgi et al.

PRD 80, 073001 (2009) + recent updates*

Appearance

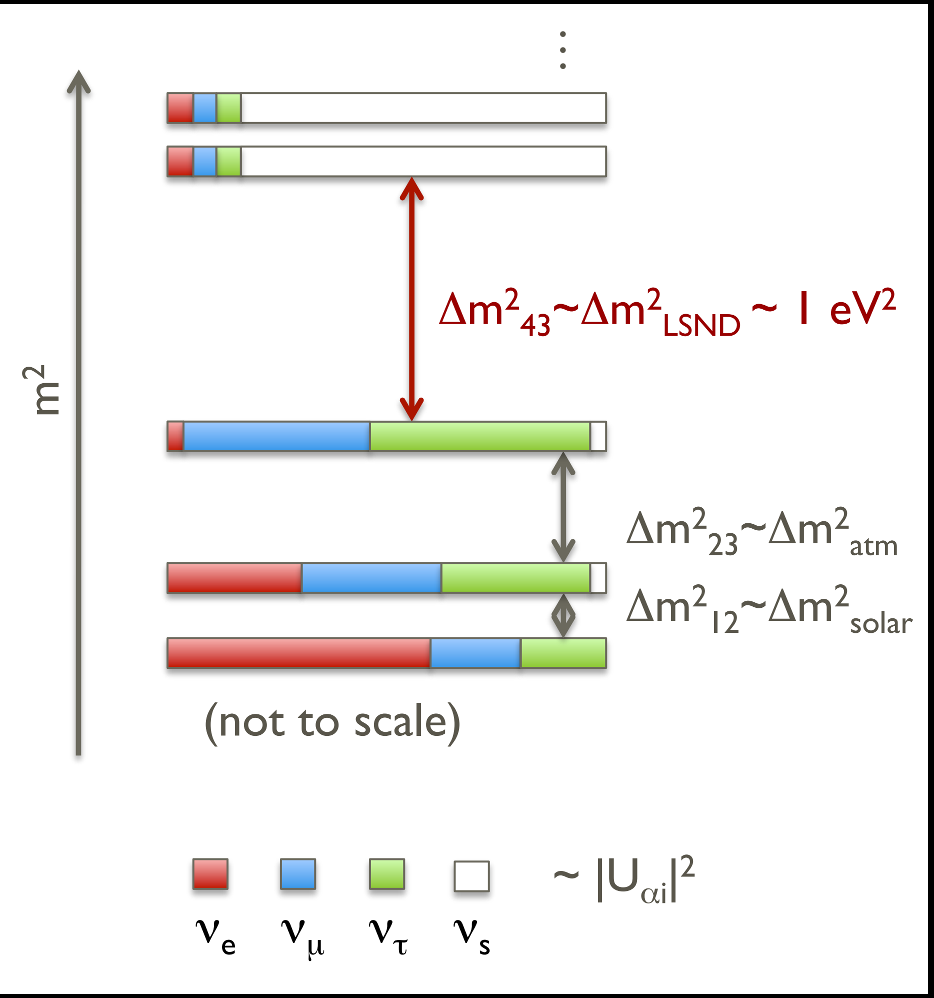
Experiment	Channel
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
MiniBooNE ($\bar{\nu}$)	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
KARMEN	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
MiniBooNE (ν)	$\nu_\mu \rightarrow \nu_e$
NuMI at MiniBooNE	$\nu_\mu \rightarrow \nu_e$
NOMAD	$\nu_\mu \rightarrow \nu_e$

Disappearance

Experiment	Channel
CCFR	$\nu_\mu \rightarrow \nu_\mu$
CDHS	$\nu_\mu \rightarrow \nu_\mu$
Atmospheric + K2K	$\nu_\mu \rightarrow \nu_\mu$
Bugey	$\bar{\nu}_e \rightarrow \bar{\nu}_e$
CHOOZ	$\bar{\nu}_e \rightarrow \bar{\nu}_e$

*: As reported by G. Karagiorgi in a recent LAGUNA General Meeting

Some Personal Comments

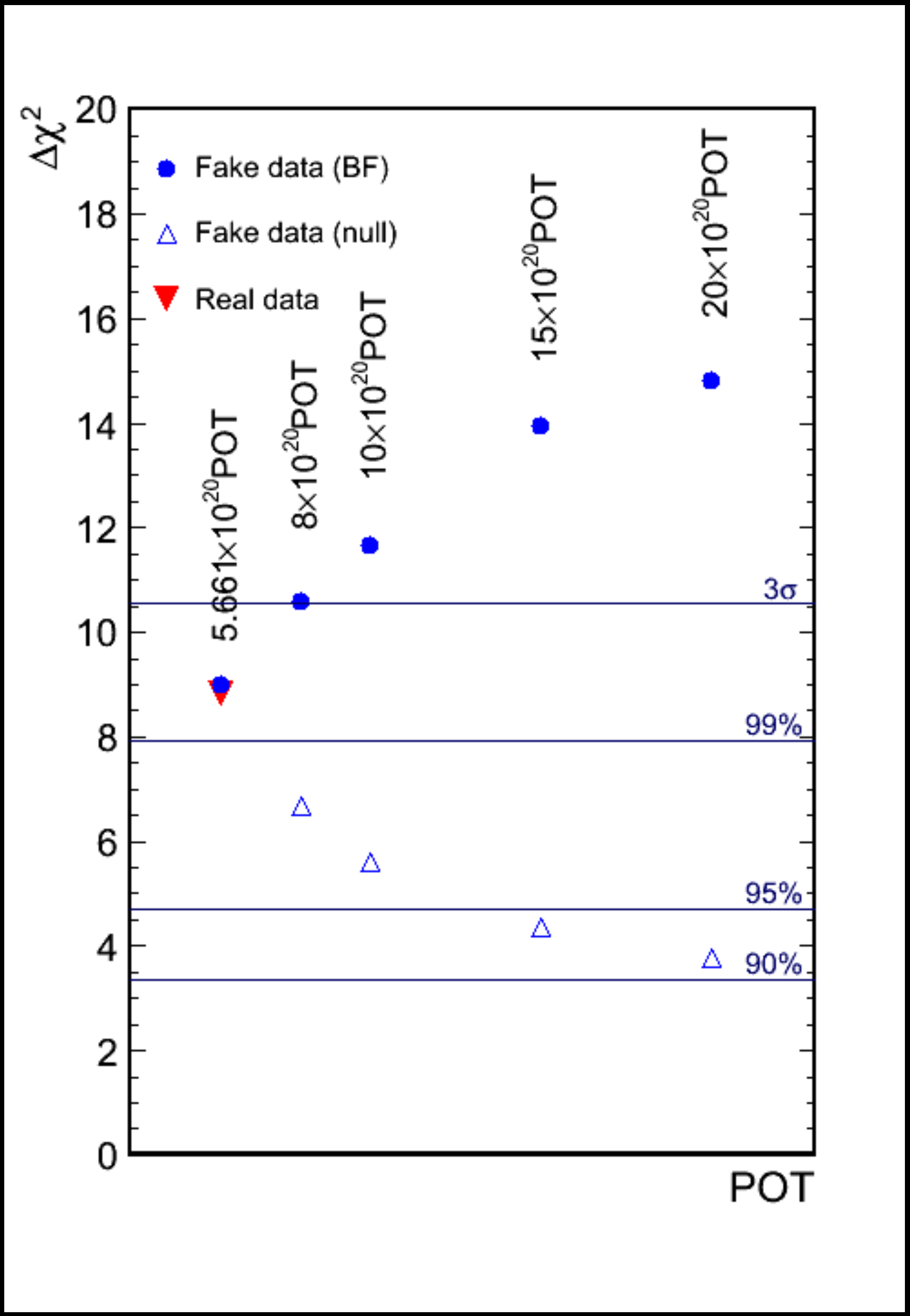


- Because signal hints primarily from antineutrino datasets (LSND, MiniBooNE), much interest in CP-violating light sterile neutrino schemes

- Need at least 2 light sterile neutrinos to have SBL CP violation: (3+2) models

- Even with CP violation, latest (3+2) fit results still quite discouraging:
  - *Large $U_{ei} \cdot U_{\mu i}$ preferred by appearance data, as opposed to disappearance (null) data*
  - *No large difference in CPC .vs. CPV fit quality (3.5 chi2 units / 1 dof)*
  - *Neutrino/antineutrino incompatibility, even allowing for CP violation*
- New reactor fluxes only alleviate (but do not solve) relatively poor fit quality
- Need something more exotic (CPT violation, neutrino decay, etc.) to explain all data?

Conclusions:



- 15 years after first first LSND claim for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, the issue is still not settled

- At such small oscillation probabilities, not an easy measurement to make!

- MiniBooNE is exploring four oscillation channels and a large L/E range covering LSND, but no clear picture (invoking steriles or otherwise) has emerged so far

- More MiniBooNE data needed:
  - New $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results this summer ($9 \cdot 10^{20}$ POT)
  - Continue $\bar{\nu}$ mode data-taking until March 2012 ($12 \cdot 10^{20}$ POT)
  - Plan to submit proposal this fall for 2nd identical detector at 200m

- More eperimental efforts definitely needed:
  - See talks at this workshop